Erosion of the beach of Historic Varadero, Cuba

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N.Kaput
M.P.T. Koenis
R. Nooij
T. Sikkema
T.P. van der Waardt

in cooperation with:

Instituto Superior Politecnico José Antonio Escheverría - CUJAE
Summary

This report handles the erosion problems on the main tourist resort of Cuba, Varadero, situated on the Peninsula de Hicacos. With a length of 22 km, a maximum width of 500 m, the Peninsula de Hicacos constitutes a natural barrier separating the shallow waters of Cardenas Bay from the Florida Strait (Figure 1-3). Measurements in the past decades have indicated a local coastal regression of 1.2 m/year on this peninsula, endangering future tourist activity and structures on the beach.

The main objectives of this research are to make an analysis of the erosion and to find a way to protect the Peninsula de Hicacos from future structural erosion.

First, extensive research to the history and characteristics of the peninsula is done, providing information on i.e. former research, bathymetry and sand characteristics. After that, possible causes for the erosion problems on the whole peninsula are identified. Identified possible causes are longshore transport gradients, sediment transportation by wind, reduction of the input of sand by the Algae Halimeda, global sea level rise and sand mining in the past.

To investigate the possible causes on its' significance, they are quantified. The longshore transport is quantified by using a software model called: UNIBEST, which was used after computations by hand with the formulas of BIJKER, CERC and QUEENS to verify the model and to get insight in the matter. The mean longshore sediment transport capacity found along the coast was about 100,000 m$^3$ per year (varying between 89,000 and 134,000 m$^3$ per year along the coast).

Wind causes about 175,000 m$^3$ of sand of the peninsula to move landward per year (using CRESS), but as it is not clear how much sand is trapped in the dunes no estimation can be done about the amount of sediment that is lost by wind transport. The input of sediment by the Algae Halimeda is neglected in this research as no sensible estimation can be given, and neglecting is the most conservative approach. Global sea level rise causes a coastal regression of 0.132 m/year, resulting in a loss of sand of 11,500 m$^3$ of the peninsula per year. Sand mining in the past could have influenced the erosion problems, but as it is almost 30 years ago, it does not cause extra erosion nowadays.
After the quantification of the possible causes of erosion for the whole peninsula, with the use of UNIBEST and observations the eroding zones were identified. Three zones were distinguished: West of the mouth of the Paso Malo near Hotel Oasis, in old Varadero (Calle 20-37) and near the rocky points between Palacio de la Rumba and Punta Chapelin (Figure 7-2). Of these eroding zones, the most critical was selected (Calle 20-37 in the town of old Varadero) and the causes of erosion in that specific zone were identified and quantified.

Hard and soft alternatives to counter the erosion are generated and a rough design is made. The alternatives that were generated are: groins, offshore emerged breakwater, offshore submerged breakwater, fishtailed breakwater, extension of Paso Malo breakwater, nourishment and maintenance. Also two non-engineering measures are handed: demolishing of structures in the dunes, and increasing the fields of Algae Halimeda. In a Multi Criteria Analysis the alternatives are weighted on four different criteria subdivided in fifteen variables. The used criteria are functionality, environment, costs, and technique & carrying out.

The Multi Criteria Analysis shows that the best hard and soft solutions are in respective order: an offshore submerged breakwater and nourishment on the foreshore of the beach in the critical zone. Therefore, these alternatives will be pre-designed.

**Nourishment**
The nourished sand will be extracted from a borrow zone used in the previous nourishments, about 10 km from the critical zone. The initial volume to be nourished is 465,000 m³ to ensure a coastline of at least 15 meters seaward of its current position and every five years another 165,000 m³ should be added to keep it that way. These volumes are determined by the use of guidelines and UNIBEST.

The time needed for the initial nourishment is five weeks; the maintenance nourishment takes two weeks. The costs of the initial nourishment are estimated on about USD 775,000 and the costs of the maintenance nourishment are about USD 330,000. When a total time of 50 years is considered and a discount rate of 5%, this leads to the total costs of about USD 1,800,000 (present day value).

**Breakwater**
The hard type solution of the erosion problem of Varadero beach is worked out as a breakwater. The simulation in UNIBEST showed that the application of only a breakwater is not sufficient to stop the erosion in the critical zone and that is why a beach nourishment program was added.
There are two alternatives made for the hard type solutions.

- A small breakwater (200 m) with a beach maintenance nourishment program
- A larger breakwater (1200 m) also with a beach nourishment program.

The costs of the total project of a breakwater of 200 m with nourishment and maintenance with in 50 years consist of:

- Construction of a breakwater of 200 m
- Initial nourishment of about 404,500 m$^3$ sand
- Every 5 years (counted from the moment of the initial nourishment) a maintenance nourishment of about 112,600 m$^3$ sand
- Every 5 year a movement of 66,900 m$^3$ sand over a distance of about 800m (replacement of sand within the critical zone)

The total costs for this alternative are approximately: USD 3,600,000.

The costs of the total project of a breakwater of 1200 m with nourishment in 50 years consist of:

- Construction of a breakwater of 1200 m
- Initial nourishment of about 173,100 m$^3$ sand
- An maintenance nourishment every 5 years (measured from the initial nourishment) of 46,000m$^3$
- Every 5 year a movement of 68,500 m$^3$ sand over a distance of about 800 m (replacement of sand within the critical zone)

The total costs for this alternative is approximately: USD 12,500,000.
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1 Introduction

1.1 General information on Cuba

The first European to glimpse the coast of Cuba was nobody less than Christopher Columbus, who on his first voyage in 1492 pronounced it the most beautiful land on earth. The island, situated most Northern in the Caribbean Sea and with a total area of 110,860 km² the biggest island of the Caribbean Sea, is still famous for its beautiful beaches and nature.

Cuba’s climate is warm and can best be described as sub- or semitropical. Two seasons can be distinguished: a wet season (May to November) and a dry season (December to April). The average rainfall is 1320 mm a year, and the average temperature is 25 degrees. With an average of once a year, Cuba is struck by tropical hurricanes, which mostly occur during the hurricane period September-November. A map of Cuba is given in Figure 1-1.
Nowadays, the Spanish-speaking Republic of Cuba has a population of more than 12 million and has a government based on communist principles. Since the government in 1980 permitted tourists from capitalist countries to spend their vacation on Cuba, tourism has grown into the island’s main income, still expanding every year. To accommodate the millions of tourists that visit Cuba every year, lots of resorts have been built near coasts. Many of these resorts are located near or in the town of Varadero, consisting of over 50 hotels with a total of approximately 23,000 hotel rooms.

### 1.2 General information on Varadero

The tourist resort Varadero Beach occupies the northern part of the Hicacos Peninsula, located in the northwest coast of Cuba at some 130km eastwards the Havana City (Figure 1-2). With a length of 22km, a maximum width of 500m, Hicacos Peninsula constitutes a natural barrier separating the shallow waters of Cardenas Bay from the Florida Strait (Figure 1-3). The total area of the peninsula is about 1,140 hectares.

![Figure 1-2 Peninsula de Hicacos](image1.png)  
![Figure 1-3 Arial photo of the peninsula](image2.png)

On the landside of the peninsula lies the town of Varadero, and on the mainland an international airport is constructed to fly in the many mainly European tourists attracted by Varadero’s beautiful beaches.

Varadero’s tourist history started in the 1870’s, when families from the nearby Cardenas began visiting. In that decade they built the first palm thatched frame houses on the northern coast, while the southern coast remained the preserve of
fishermen. The beach’s fame grew however, luring visitors from Havana. The year of 1915 marked the inauguration of the town’s first resort: Hotel Varadero.

In 1950 Hotel Internacional was constructed. That sparked a development boom that continued until the Cuban Revolution in 1959. Dozens of hotels arose from the one end of Varadero to the other, complete with golf courses and gambling casinos. Parallel to this hotel development was growing what it is now called the "historic Varadero", where a great part of the population that supported the tourist activity was settled. In this sector of the beach the dune field was literally invaded by hotels and the summering houses.

This development came to a halt after the Revolution, and the first hotel built since then was built in 1990. Since then, many other hotels and tourist facilities have been developed. Within the scope of the current Cuban efforts for the increment of the tourist activity in Cuba, there are also many construction plans for the future.

Nowadays Varadero plays a significant role into the national economy. Income generated in Varadero is about 400 million dollars a year, 37% of the total income from tourism in Cuba.
2 Problem description

2.1 Problem definition

Although the Peninsula de Hicacos may seem to be an idyllic place, it's not free of problems. For almost 40 years there has been an erosion of the beach along the peninsula. It is suspected that this erosion is due to the effects of human activity (use of sand for construction purposes) and the subtle change of the climate that created more occurrences of higher waves, although other more complex influences cannot be excluded directly.

This erosion caused some serious loss of sand over the years, which now results in a structural regression of the coastline. If the erosion won't be stopped or measures are taken to counter the effects, this decrease will eventually result in the threat of the hotels built next to the beach. Because the tourist industry is growing more and more in Cuba nowadays as the main source of national income, it will be necessary to protect beach resorts such as in Varadero.

Although similar problems occur around the world, it is difficult to come up with a solution for this particular problem. Not only the technical requirements have to be taken in account, but also the economic situation of Cuba plays a role: such a solution has to be profitable according to Cuban standards and possible to be constructed and maintained with the available funds and equipment.

2.2 Main objective

The main objectives of this project are to get an analysis of the erosion and to find a way to protect the Peninsula de Hicacos from future structural erosion.
2.3 **Sub objectives**

To come to a solution to prevent structural erosion of the peninsula, it is necessary to take into account several different topics:

- Causes of the structural erosion.
- The amount and direction of the actual sediment transport; which effects are the main mechanism for the sediment transport.
- When structural erosion is proven after the analysis, and the causes of erosion can be appointed, solutions can be proposed to eliminate the erosion that endangers the peninsula.
- Hard solutions (i.e. groins or seawall) as well as soft solutions (i.e. beach nourishment once in several years). In the final advice for the best solution, the economic situation and organizational structure of Cuba will be of great significance.

Another sub objective of the project is to propose a methodology for the Cuban engineers to deal with erosion problems in general.

2.4 **Structure of the report**

The investigation will start with relevant research in chapter 3. In chapter 4 the possible causes that threaten the beaches of the peninsula will be determined and quantified in chapter 5 and 6. A most critical zone will be selected in chapter 7, for which solutions will be presented in chapter 9. One soft type solution and one hard type solution will be further investigated in chapter 10 and 11. The 12th chapter describes a methodology for engineers to deal with erosion problems. The conclusions and recommendations of the investigation are presented in chapter 13.
3 Research

3.1 Introduction

This chapter gives important information of the project and describes the gathered research in relation with the erosion problem in Varadero. The information in this chapter is gathered from information obtained from the Institute of Oceanology, the Malecon project and from several other international sources.

3.2 The project area

The Peninsula de Hicacos has a total length of 22km with a maximal width of 500 m. The peninsula is shaped in a northeastern direction and has a projection of 30° in direction. The beach of the peninsula that borders the Strait of Florida mainly consists of very fine coral sands. In the bay of Cardenas, south of the peninsula a large mangrove forest is present.

The beach of the peninsula can be divided in 3 different sections (Figure 3-1). This division is made after two former nourishment programs, one in the Western part and another in the Eastern part, executed in respectively 1998 and 2003. Between these three sections different characteristics of the beach can be distinguished.
The names of hotels and resorts on the peninsula are often referred to in this report. The location of these hotels is given in Figure 3-2, and in Appendix 1.
3.2.1 Section 1

This section covers the area of nourishment in 1998. The area that has a coastline of approximately 11.5km, it runs from hotel Oasis (nr. 1 in Figure 3-2) to hotel Melia Las Americanas (nr. 13 in Figure 3-2).

East of hotel Oasis, the Paso Malo channel has been constructed a few decades ago, the exact datum is not known. Two large breakwaters (Figure 3-4) mark the entrance with a length of approximately 110 meters seaward.

In section 1, historic Varadero covers a large area. There are two main roads in this town; the Autopista del Sur (Southern Highway), and the Avenida Primera (First Avenue). Between these roads perpendicular to the coastline the streets are numbered from Calle 1 – 69 (Street 1 to 69). A situation map of the town is given in Figure 3-3. In this town many houses and hotels are built very close to the beach (Figure 3-5).

Figure 3-3 Map of Historic Varadero (source: Lonely Planet)

Figure 3-4 Breakwaters in Paso Malo (Sept. 2003)

Figure 3-5 Beach in historic Varadero (Sept. 2003)
The beach on the peninsula east of the Paso Malo entrance to historic Varadero is called: Playa Kawama. The beach in the town is called: Playa Varadero. The rocky cliffs at hotel Las Americanas (nr. 13 Figure 3-2) are called Penas de Bernardino.

3.2.2 Section 2

This section is called 'Los Tainos' and covers a coastline of approximately 8km. No coastline protection has been done in this area. The section runs from hotel Las Americanas (nr. 13 Figure 3-2) to Punta Rincón Frances.

The coast in this area can be qualified as rocky. Some bays can be distinguished, with rocky borders and small sandy beaches (Figure 3-6).

![Figure 3-6 Rocky coast in section 2](image)

3.2.3 Section 3

This section is Called 'Punta Hicacos' (Endpoint of Hicacos). A nourishment project was executed in September 2003 to protect the beach for the next 10 years (Figure 3-7).

In this section a protected dune area is appointed. No human intervention may be done here, so the dune and its original vegetation has remained intact. Two large 5-star hotels are present; three hotels more are being constructed in 2003.

A sandy beach is present in the whole section.
3.2.4 Summary

The beach of the peninsula can be divided in 3 different sections (Figure 3-1). This division is made after two former nourishment programs, one in the western part and another in the eastern part, executed in respectively 1998 and 2003. In these three sections different characteristics of the beach can be distinguished.

Section 1: 11.5km coastline, between hotel Oasis (Figure 3-2. nr 1) and hotel Las Americanas (nr. 13 in Figure 3-2). Nourishment took place here in 1998. In this section historic Varadero occupies a large area. In this section a sandy beach is present.

Section 2: 8Km coastline, from hotel Las Americanas (nr. 13 Figure 3-2) to Punta Rincón Frances. The section contains rocky points. No coastal protection has been done here.

Section 3: 4km coastline on the northeast point of the peninsula. A nourishment project was executed in September 2003.
3.3 History of the Varadero project

The Institute of Oceanology of Cuba was responsible for all former investigations of the erosion of the peninsula. The institute showed an erosive trend of the entire beach along the peninsula for almost 30 years, it has estimated an erosion rate of the beach by comparison of beach profiles over the years.

The conclusions that were drawn were:

- A loss of 50,000m$^3$ sand per year.
- Regression of the beach strip of 1.2m per year.

As a result of the investigations of the institute the following erosion causes were identified:

- Location on the dune field of more than 150 houses and hotels along some 10km of beach in the so called "historic Varadero".
- Sand extractions of 990,000m$^3$ for the building industry between 1968 and 1978 in areas of the submarine shelf. The earlier assessed volumes of extractions including the dune field area reached an average volume of up to 1,000,000m$^3$.
- The breakwaters at Paso Malo.
- The continuous rise of sea level associated with global sea level rise.

Beach protection measures have been done to solve the problems of erosion and its generating factors, and also to recover the eroded sectors of the beach. The protection measures adopted in Varadero were aimed to meet both requirements: coastal management and nourishment of the beach.

3.3.1 Management of the coastal zone

The forbidding of sand extractive practice and the elimination of about 50 old facilities wrongly located on the dune were the main actions. As another important measure for the preservation of the beach a "line of building control" was established in those sectors in which new tourist investments are developed. Its goal is to guarantee the preservation of the natural dune field.
Experience obtained in Varadero has been advantageously applied to other beaches of the country and it was taken into account for the elaboration of the Decree No. 212 "Coastal Zone Protection ", put into use since the year 2000.

3.3.2 Nourishment of the beach

After evaluation of different coastal engineering techniques, artificial beach nourishment was selected in 1985 as the best option to guarantee the maintenance of the natural physical conditions, as well as its landscape.

From 1987 to 1992 several small scale nourishment programs were carried out. However, insufficient nourishment made possible that hurricanes Joseph and Lily caused serious damages to the beach and partially or totally destroyed tourist facilities in 1996. An evaluation of the physical conditions of the beach after the penetration of the sea in 1998 demonstrated that its deterioration had reached extreme limits. Beach erosion became the main factor that impacted negatively the commercial activities of tour operators.

Taking into account the critical state of the beach, the Ministry of Tourism and Ministry of Science, Technology and Environment (CITMA) decided in 1997 to execute a new nourishment project. The technical project was elaborated by the Institute of Oceanology and after a study of Environmental Impact, received the Environmental License and the corresponding authorizations, being ready for execution. In the summer of 1998, Dutch company Blankevoort nourished a volume of 1,087,000m³ sand on the 11.5km beach in section 1 (Figure 3-1). The sand was obtained from a borrow area 19km from the beach.

In September 2003, another nourishment project is in execution: Beach nourishment of 4km coastline in section 3 (Figure 3-1). The total volume of dredged sand is 460,000m³. This total is based on principles to compensate losses of sand in the dynamic system (170,000m³), regression of the coastline in 30 years, and the required mean beach surface area of 10m²/tourist.

3.3.3 Maintenance after 1998

Although the nourishment in 1998 is remarked as a success, some sections on this beach remain very vulnerable. Maintenance measures are still required every year in order to protect structures near the shore and guarantee a sufficient surface area of
sandy beach for the visitors. These contain a wide range of measures, varying from
the creation of an artificial breaker zone made of sand bags near Hotel las
Americanas, the dredging of material from the second sand bank to the shore
between Calle 23 and 36 in historic Varadero, to extraction of sand east of the Paso
Malo breakwaters to nourish the Oasis beach (Figure 3-8).
All this measures are not permanent and have to be repeated each summer.

Figure 3-8 Sand extraction East of the Paso Malo for annual maintenance

3.3.4 Monitor program

A monitoring program of the beach profiles in section 1 (Figure 3-1) has been
developed after the nourishment project in 1998. Researches gave report about sand
loss rate and main tendency of long-shore and cross-shore sediment transport.

A systematic control on the morphologic varieties of the beach is established in 34
profiles. In the period from 1998 to 2002 monthly measurements of the beach
profiles were done. An assumption is made that the profile at the measurements is
representative for the area in which it is located.

The measurements done in December 2001 affirm that three years after the
nourishment, 17% of the sand was lost.
3.3.5 Critical zones

In this report further investigation will be done to determine the location of critical zones and the causes of the erosion in these zones. The results from the Institute of Oceanology are given here to be able to compare them with the results of the further investigation.

On the peninsula the Institute of Oceanology has defined five critical zones. In these zones the erosion causes the most threat to the existing structures and beach.

These critical zones are:

1. Oasis beach (Figure 3-2, nr. 1).
2. Approx. 200m in historic Varadero between hotel Kawama and Calle 7 (Figure 3-2, nr. 1).
3. Both sides of rock of Hotel Melia Varadero. (Figure 3-2, nr. 13)
4. The beach at hotel Sol Palmeras. (Figure 3-2, nr. 15)
5. Approx. 1000m in historic Varadero between Calle 23 and 36 (Figure 3-3).

The Institute of Oceanology assumes the following causes for the erosion problems.

Erosion in critical zone 1:
The entrapment of sediments caused by the two breakwaters at the entrance of the canal Paso Malo.

Erosion in critical zone 2:
The bathymetry and configuration of the sea bottom that makes this section a convergence point of waves.

Erosion in critical zone 3 and 4:
Submerged terraces of rock situated nearer to the surface than terraces in other areas. Signs of unveiled rock are visible in this zone.

Erosion in critical zone 5:
This zone is situated in the center of historic Varadero where seawalls are constructed very near the shore. Here is where erosion is most severe. First indications after hurricane Michelle show escarpment on the dune with a height of 3 m and rock surface is still visible on the foreshore and inshore on up to 1000m in seaward directions.
3.3.6 **Summary**

The Institute of Oceanology, responsible for all former investigations on the erosion of the peninsula measured that at the peninsula of Hicacos an annual sand loss of 50,000 m$^3$ sand takes place. This means a regression of the beach strip of 1.2 m per year.

Several causes of erosion were identified by the Institute such as building on the dune, sand extraction, breakwaters of Paso Malo and sea level rise.

After evaluation of different coastal engineering techniques, artificial beach nourishment was selected as the best option to guarantee the maintenance of the natural physical conditions. Therefore, several nourishment programs were carried out. A monitor program was introduced in 1998 to evaluate the nourishment of that year. In this evaluation the institute points out 5 critical zones where erosion is most severe in Varadero. Maintenance measures are required every year in order to compensate further erosion.
3.4 Bathymetry

3.4.1 Introduction

In this chapter the bathymetry of Varadero beach will be described and some explanation will be given about the cross-shore profiles. Secondly something will be said about the vegetation below the water surface and the sand characteristics will be discussed.

3.4.2 Presumptions about the bathymetry

To model the beaches of Varadero, one has to make some assumptions. There is no spot along the beach where the bathymetry is the same, because in the eastern parts the sea stays longer shallow than in the western parts where the sea becomes very deep within a few hundred meters. Because of this the peninsula is divided into areas where the bathymetry and wave conditions are comparable.

- From the mouth of the Paso Malo till Kawama the orientation of the coast is different in comparison with the other sections of Varadero beach. The presence of the Paso Malo breakwater and the different coastal angle are the reasons why the profile in this section is unique.
- From Kawama to Punta Frances the coastal angle is the same, but because of some irregularities in the dune (houses, rocks etc.) the coast is divided in multiple sections and every section has got its own bathymetry (profile).

A beach profile has a practical seaward limiting depth, where the wave conditions can no longer change the profile. Sediment will still move back and forth, but there is no perceptible change in depth. This critical depth or closure depth is calculated with the next formula$^1$:

$$d_c = 1.6 \cdot H_{s,12}$$  
(Formula 3.1)

Where:

$H_{s,12}$ is the significant wave height which occurs 12 hrs/yr on average.

$^1$ Hallermeier (1981)
This wave height is determined with the information of the Global Wave statistics. With the formula the critical depth was calculated to be at a depth of 11.2m below the mean water surface.

The beach profiles are derived from measurements from the Institute de Oceanology. They had done some measurements about the beach profiles and put it in a drawing program, called TOPOCAR. The profiles from TOPOCAR are very good to get an idea of the shape of the dunes, but are insufficient when one is interested in the bottom profile below the water surface, because the measurements were taken till a very small depth.

The beach profiles change throughout the year due to the change of the wave climate. If you want to make a model you have to determine a mean, representative profile. According to the information from TOPOCAR and other profiles from the Institute of Oceanology the profiles of the month March 2001 are determined as the representative profiles. From this year on, the most recent complete information could be obtained. Some profiles stopped already in shallow water, but were extended with help of the charts from the British Admiralty.

The profiles used in the calculations are given in Appendix 2. In these figures the bottom level is plotted to the distance from the measurements points to the dune. Both have the unit of length (m) and the mean water level is said to be on the zero meter bottom level. This way the figures show the actual bottom contour below the water surface.

### 3.4.3 Marine vegetation

The Institute of Oceanology has over the years analyzed several sand samples throughout the peninsula. These samples indicated that the sediment deposits of Varadero beach are made up of biogenic carbonated sand and although some differences remain, the fraction 0.25-0.5mm is considered as the predominant fraction.

The biogenic composition also showed some differences, a sampling pattern of the beach consisted of 40% of calcareous fragments of Halimeda algae, 25% of mollusks, 25% of foraminifers, 5% of corals and others organisms and 5% of inorganic material. Being the main source of sand, the Halimeda Algae (Figure 3-9) consists 89% of carbonate. This plant grows on the seafloor with a height of approx. 0.5m. The algae grow in fields (patches) that are situated starting approx. 2-4Km northeast of the peninsula.
An estimate given by the Institute of Oceanology of the sand production is 10 kg/m²/year.

3.4.4 Sand characteristics

Sand samples were taken by the Institute of Oceanology in different profiles along the coast of the peninsula (Figure 3-11) and granulometric tests were conducted. For the evaluation of the nourishment that took place in June 1998 a comparison of the mean sand diameters in the different profiles were compared before and after the beach nourishment (Appendix 3). It is clearly visible that the granulometry along the area has changed from the uniform situation directly after the nourishment. In the column corresponding to samples taken in April 2000 the profiles in which the mean sand diameter have diminished are colored in blue. The profiles where the mean sand diameter has increased are colored in yellow. The results are also represented graphically in Figure 3-10.
Figure 3-10 Comparison of the sand samples taken along the nourishment zone of 1998 (source: Institute of Oceanology)

It can be noticed that in the borders of the nourishment-area (for example: Duna E and PN-24) the mean sand diameter tends to diminish over time.

The Institute of Oceanology identifies the following possible causes for this phenomenon:

- As the finer particles of the nourished sand are more easily transported long shore, they arrive at the borders of the nourishment zone and mix with the native sand thus diminishing the average grain size diameter.
- Before the nourishment of 1998 the area next to Paso Malo until Kawama presented the highest mean sand diameter of the peninsula (larger mean sand diameter than the sand used for the nourishment $D_{50}=0.38\text{mm}$). So it is logical that the granulometry in this area diminished after nourishing with sand of slightly smaller diameter.

In addition to the conclusion of the Institute of Oceanology the following can be added:

- Places where average grain size increased most probably indicate erosion of the beach, and places where grain size decreased indicate accretion. Since the finer particles get eroded first.
Wind blowing along the peninsula from an eastern and north-eastern direction may have displaced the smaller grain particles.

Although the sand used for the nourishment had a $D_{50}$ of 0.38mm, there were differences in average grain size diameter inside the borrow area (South of Cayo Mono). So variation of the grain size of the nourished sand could promote differences of granulometry along the nourished area.
Figure 3-11 Distribution of the mean sand diameter in January 2002 along the nourishment zone (source: Institute of Oceanology)
Five sand samples were taken along profile of Duna M during this project. (Figure 3-13) with the purpose to verify and compare granulometric data obtained from the Institute of Oceanology.

The samples were taken at different points along the profile and displayed in Table 3-1.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Location along the Profile Duna M</th>
<th>Distance from shoreline (m)</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Beach</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>First submerged bank</td>
<td>150</td>
<td>1.5-2m</td>
</tr>
<tr>
<td>3</td>
<td>Between the first and second bank</td>
<td>300</td>
<td>4-5m</td>
</tr>
<tr>
<td>4</td>
<td>Second bank</td>
<td>400</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Seaward second bank</td>
<td>500</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 3-1 Sand samples taken by project group CF-15, September 2003

These samples were analyzed at the Geotechnical laboratory of the CUJAE. The results are presented Table 3-3.

<table>
<thead>
<tr>
<th>Sample</th>
<th>D90 (mm)</th>
<th>D50 (mm)</th>
<th>D10 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beach</td>
<td>0.7</td>
<td>0.3</td>
<td>0.14</td>
</tr>
<tr>
<td>1st bank</td>
<td>0.6</td>
<td>0.25</td>
<td>n.a.</td>
</tr>
<tr>
<td>1st-2nd bank</td>
<td>0.6</td>
<td>0.26</td>
<td>0.12</td>
</tr>
<tr>
<td>2nd bank</td>
<td>0.6</td>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>behind 2nd bank</td>
<td>0.7</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Average</td>
<td>0.64</td>
<td>0.312</td>
<td>0.1475</td>
</tr>
</tbody>
</table>

Table 3-2 Results from the granulometry at the Geotechnical Laboratory, CUJAE

It is interesting to notice that along the profile the sand diameters seems to vary, noticeably smaller grain sizes on the sandbanks and larger behind the second bank. However, to make conclusions about variance of sand diameters along the profile more measurements are recommended, also along more profiles from the coast.
3.4.5 Fall Velocity

The fall velocity is the maximum velocity that a particle reaches when the (retarding) drag force on the particle just equals the (downward) gravitational force. It is an important parameter in coastal engineering and is a function of the particle's size shape and density; as well as the fluid density, and viscosity, and several other parameters.

In the evaluation report of the 1998 nourishment the Institute of Oceanology uses a value of 0.0455m/s for the fall velocity taking a mean sand diameter of Varadero of 0.26mm.

After performing the granulometry of the sand there are several ways to determine the fall velocity to verify this value:

The Coastal Engineering Manual\(^1\) (CEM), determines the fall velocity through Figure III-1-6 (Appendix 4), which shows the fall velocity as a function of grain diameter and water temperature for quartz spheres falling in both water and air. In the CEM the fall velocity depends on \((\rho_v/\rho-1)^{0.5}\). For quartz sand grains in fresh water, this factor is about 1.28. The data in Figure III-1-3 is portrayed for measurements in freshwater so for quartz grains in ocean water the factor is reduced to 1.25 because of the slight increase in density of saltwater. Using this Figure the following fall velocities are obtained.

\[
D_{50} = 0.26\text{mm (Oceanology), } w_{50} = 0.04 \text{ m/s} \times (1.25/1.28) = 0.039 \text{ m/s} \\
D_{50} = 0.31\text{mm (Project group CF-15), } w_{50} = 0.045 \text{ m/s} \times (1.25/1.28) = 0.044 \text{ m/s}
\]

Comments on the use of the CEM:
Figure III-1-3 is meant for quartz sand (\(\rho = 2648 \text{ Kg/m}^3\)), the sand at Varadero is biogenic carbonated sand (\(\rho = 2700 \text{ Kg/m}^3\)) this difference is not taken into account.

The computer program CRESS\(^2\) routine 411 (Properties of sea water and sediment) also calculates the fall velocity with an empirical formula of van Rijn. Results are shown in Figures 3-12 and 3-13.

---

\(^2\) IHE Delft (2000), CRESS version 8
Figure 3-12 CRESS interface routine 411 for D_{50}=0.26mm

Figure 3-13 CRESS interface routine 411 for D_{50}=0.31mm

Comments on CRESS:
The salinity of the seawater at Varadero is not known, an assumption of 30 ppt (parts per thousand) was made.

Evaluation

The results of the calculations are summarized in Table 3-4 and 3-5:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Institute of Oceanology</th>
<th>This project</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_{50}</td>
<td>0.33 mm (Duna M April 2000)</td>
<td>0.31mm (Mean for profile Duna M, September 2002)</td>
</tr>
</tbody>
</table>

Table 3-3 Comparison of the D_{50} between the Institute of Oceanology and Project group
### Table 3-4 Comparison of the Wf between the Institute of Oceanology and Project group

<table>
<thead>
<tr>
<th>Institute of Oceanology</th>
<th>This project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wf 0.0455m/s (using D50= 0.26mm as mean for Varadero)</td>
<td>According to CEM:</td>
</tr>
<tr>
<td></td>
<td>0.039 m/s (D50= 0.26mm)</td>
</tr>
<tr>
<td></td>
<td>0.045 m/s (D50= 0.31mm)</td>
</tr>
<tr>
<td></td>
<td>According to CRESS:</td>
</tr>
<tr>
<td></td>
<td>0.040 m/s (D50= 0.26mm)</td>
</tr>
<tr>
<td></td>
<td>0.049 m/s (D50= 0.31mm)</td>
</tr>
</tbody>
</table>

Comparing the results of the Institute of Oceanology with the measurements and calculations from this project it can be concluded that granulometry and fall velocities are not very different.

For further calculations in this report the mean sand diameter of 0.31mm is used.

This results in the fall velocity of 0.045m/s according to CEM. The reason for using CEM is the uncertainty in the value of the salinity used in CRESS.

### 3.4.6 Morphological variations of the beach profile

In 1978 the Institute of Oceanology started investigating the dynamics of the coast of the Peninsula de Hicacos.

For beaches situated in the northeastern part of Cuba winter is the period associated with storms, when cold fronts are formed with strong winds from the 4th quadrant. The profile in that period is characterized by the absence of the berm, a straight surface with gentle slope and regularly an upward concave. During the summer months the beach profile recuperates itself. The beach profile in the summer is characterized by a well-defined berm which is downward concave and its surface undulated. The slope is slightly inclined landwards and sharply inclined seawards.

---

Sonu (1973) concluded that the cycles of the beaches are primarily dependent of the disturbances from continuous storms. This is evident in the case of Varadero where the maximum erosion is measured in the winter months. In this period continuous storms originate because of the arrival of the cold fronts, causing waves at the coast with a height of over 1.5m. In general, the frequency of the cold fronts does not permit remodeling of the profile between storms, that is why the typical winter profile can develop. The profile of maximum erosion can form itself in a very short time.

The maximum erosion and the configuration of the winter profile are primarily formed in the months December, January and February. In the period of March until October or November the profile recuperates itself and the summer profile is formed.

Sonu (1973) observed that associated with the rhythmic topography of the coast there are profiles with erosion characteristics in a very short distance of other profiles with characteristics of accumulation. This demonstrates that the behavior of a profile in a particular moment and place is strongly influenced by the configuration of the coastline. There have not been studies on rhythmic topography of the coast of Varadero but its presence has been observed on different occasions.

This is not surprising as Varadero beach has the necessary conditions for the forming of this rhythmic topography:
- The slight slope of the bottom
- The abundance of beach sediment
- The predominance of the oblique wave action.

The name 'rhythmic topography' was suggested to distinguish this type of formation of the ordinary 'cups' of the beach which are smaller in size and depend primarily on the submerged part.

In Varadero it has been observed that in some occasions the land penetrating part of the peninsula, sinusoidal coastline (valleys) have originated at places with structures on the beach. This causes that the waves break on the structures, causing erosion. This situation can be formed during the summer when the beach is generally affected by the accumulation of sand.

---

1 From Sonu, Ch. J. (1973): Three dimensional beach changes. J. Geol., 81:42-64.
An example of this is the case at Villa La Herradura (Figure 3-14) where frequently a valley is formed and waves collide with the building wall, which causes wash-out of the beach profile and emergence of underlying rock.

![Wave damage Hotel Villa Herradura, September 2003](image)

**Figure 3-14 Wave damage Hotel Villa Herradura, September 2003**

So, Juanez concludes that constructions close to the shoreline are not only prejudicial during storms but also during periods of accumulation.

Changes in the orientation of the coastline are another factor that significantly influences the beach profile. It must be taken into account that the profiles obtained from 'La Conchita' until 'Rincon Frances' are in a coastline that has an orientation of 30 degrees with the equator.

In that area the erosion is produced during the cold fronts, when the winds blow from the 4th quadrant and generate waves directly on the coastline. (Figure 3-15).

![Effect of the waves on the Peninsula in the winter](image)

**Figure 3-15 Effect of the waves on the Peninsula in the winter**
3.4.7 Summary

The bathymetry of Varadero beach is described and the cross-shore profiles of the different sections along the entire coast of the peninsula are presented in Appendix 2.

The sediment deposits of Varadero beach are made up of biogenic carbonated sand, the predominant sand fraction ranging from 0.25-0.5mm. The main source of sand, the Halimeda algae has an estimate production of 10 kg/m²/year.

Comparing the results of the Institute of Oceanology with the measurements and calculations from this project it can be concluded that granulometry and fall velocities are not far apart. For further calculations in this report the mean sand diameter at Varadero of 0.31mm is taken to be the most actual data available, resulting in the fall velocity of 0.045m/s according to Figure III-1-6, Coastal Engineering Manual.

The morphological variations of the Peninsula de Hicacos are closely related to the periodical changes in the hydrological regime of adjacent waters and the spatial differences in the orientation and configuration of the coastline. An abstract table with the four types of variations and their direct effect on the beach profile, form part of the results.

3.5 Geology of the peninsula

The Peninsula de Hicacos consists of a natural barrier separating the shallow waters of Cardenas Bay from the Florida Strait. The peninsula used to be a group of separated small limestone islands. With the transport of sand produced by Algae fields the gaps between the islands were filled, eventually resulting in a peninsula.

The northern coast consists mostly of extensive sandy beaches, separated by some limestone massifs. In section 1 (Figure 1-1, Appendix 1) the beach profile has been intensively modified by the construction of tourist facilities.

In the places, where natural conditions are still preserved, the coast profile includes the contemporary sandy-accumulative beach, with a berm that does not exceed
1-1.5 m above sea level and a sandy ridge reaching a height of 4.5 m covered by dense vegetation. An example of such structure is observed in the Sol Palmeras hotel profile in the central part of the Peninsula, as is shown in the Figure 3-17.

![Figure 3-17 Schematic profile of the shore line in the zone of the Hotel Sol Palmeras](image)

The shown profile corresponds to the accumulative coast. It identifies the zone of the littoral contemporary deposits of the Holocene, (the berm and the post-beach). The zone of the earlier Holocene deposits includes the old storm ridge made up of sand and the land inwards accumulative sandy terrace. The structure and distribution of the coral barriers as well as of the sandy deposits are represented in the profiles shown in Figure 3-18.
Figure 3-18 Cross section of the submarine shelf

In the profiles, three clearly defined terrace levels can be noticed: the first one with lower part of the juncture down to -26m. The other two having different high levels to -5m, -6m and -3m, -4m respectively, located no far offshore.

3.5.1 Summary

The Peninsula de Hicacos consists of a natural barrier separating the shallow waters of Cardenas Bay from the Florida Strait and used to be a group of separated small limestone islands that were connected over time by sand transported from algae fields, eventually resulting in a peninsula. The northern coast of the peninsula consists mostly of extensive sandy beaches, separated by some limestone massifs. Cross sections show sandy basins and terraces on different depths.
3.6 Climate

As said in the introduction, Cuba’s climate can be best described as semi- or subtropical with little seasonal variation. It is very moist, with an average humidity of 78%. In the wet season, humidity can rise up to values of more than 90%. Influenced by the warm Gulf Stream and by the North Atlantic pressure zones, wind is almost always blowing from the northeast.

In this Paragraph, a description of Cuba’s useful meteorological variables is given.

3.6.1 Temperature

Cuba’s mean annual temperature is 25.2°C, with an average sunshine of 8 hours per day throughout the year. July and August are the hottest months of the year with a mean temperature of 27°C; January is coldest with a mean temperature of 22°C.

Highest temperatures in summertime nevertheless can run up to far more than 35 degrees. Because the wind is most of the times blowing from the northeast, the southern part of the island is usually warmer than the northern part. There is also a little variation in temperature between the east and the west of the island, resulting in a higher mean temperature in the southeast.

Lowest temperatures, infrequently falling below 10°C, occur during winter time when severe cold fronts sweep down into the Gulf of Mexico. It has never frozen since temperatures are measured: the lowest temperature ever measured is 0.6°C. Maximum temperature ever measured is 38.6°C.

In Varadero, maximum mean monthly temperature is almost 32°C and in winter time minimum temperature falls to 19 degrees (Figure 3-19).
Sea water temperature vary from 26°C in winter to 32°C in summer, and due to the varying influence of the Gulf Stream the northern coastal water usually is cooler than the southern (Figure 3-20)
3.6.2 Rainfall

Total annual rainfall in Cuba is 1320 mm, and it rains 85 to 100 days a year. Most of the rain, about 80%, falls during the wet season when humidity rises to very high values. Showers most of the time don’t last long; after half an hour the sun comes back again. On the other hand, severe storms and downpours can also occur.

Central and western regions of the country experience a three to five months dry period known as ‘La Seca’. February through April and December are the driest months. Nonetheless, there are heavy winter downpours associated with cold fronts sweeping south from North America.

The Atlantic coast is slightly rainier than the southern coast, but the mountains receive the highest rainfall, sometimes up to 3000 mm per year.

Most heavy rainfall is during hurricanes; during hurricane Michelle (2001) an amount of 234mm in 24 hours is measured.

3.6.3 Wind velocities and directions

3.6.3.1 Cuban sources

Not much information is available on the subject of wind velocities and directions in the neighborhood of the Peninsula de Hicacos. In 1978 and 1979, wind velocities from the directions west to east-northeast were measured at the airport of Varadero, with the results as shown in Figure 3-21. Also it was indicated that about 3% of the wind comes from west to north-north-west direction, and about 30% from the north to east-north-east direction.
Unfortunately, no information on other directions was available.

### 3.6.3.2 Other sources

No global information on wind directions has been found. Though, from global wave statistics, wind velocities can be obtained using the significant wave period. This can be done with formula 3.2:

\[
\frac{g}{2 \pi \cdot T_{1/3}} \cdot T_{1/3} = U_{10}
\]

(Formula 3.2)

In which:

- \( g \): gravitational constant
- \( T_{1/3} \): significant wave period
- \( U_{10} \): wind speed at 10 meter above the surface

Because wave directions are equal to wind directions, the distribution of wind directions can also be taken from the global wave statistics. When combining the
distribution and the calculated velocities, you can obtain the distribution of wind velocities and directions. There has to be remarked, that by doing that, the assumption is made that all the recorded waves are windwaves, and therefore no swell waves appear.

In the global wave statistics however, only the mean zero crossing periods (the time interval between upward or downward zero crossings on a wave record, \( T_z \) or \( T_m \)) are given, so the significant wave period have to be calculated.

Wave periods do not allow conversion with factors related to a distribution function. Instead such factors depend on the spectral shape. Wave analyses by Goda (1979) have revealed a range for various conversion factors for the various spectra.

So first there has to be determined what wave spectrum fits the Cuban coast best: the two spectra that are looked at are the Pierson-Moskowitz spectrum and the JONSWAP spectrum. Because north of Cuba the fetch is limited, it is clear that the JONSWAP spectrum fits best.

For the JONSWAP spectrum, Goda gives the following conversion factors: \( T_m/T_p = 0.79 \) to \( 0.87 \) and \( T_s/T_m = 1.13 \) to \( 1.33 \). When making use of the second conversion factor, the significant wave period can be calculated. With this significant period, wind speed at 10m height can be calculated with formula 3.2. In the calculations a conversion factor of 1.23 is used for \( T_s/T_m \).

The results are shown in Figure 3-22.
3.6.3.3 Evaluation and conclusion

Wind information obtained from the airport of Varadero is old and does not include all wind directions. Nevertheless, the point where the measurements are taken is very close to the Peninsula de Hicacos and should therefore be representative for winds on the peninsula.

Global wave statistics do provide information on wind directions as well as a distribution of velocities for all directions and are therefore very complete. Also the number of observations is very large. On the other hand, the areas in which data for global wave statistics is collected are very big. Differences in winds within the areas are not included, and therefore the wind information obtained from the global wave statistics is very general. Nevertheless, it shows little difference with the data of the airport.

Because of the lack of more information, the wind information obtained from the global wave statistics should be used when the wind information obtained from the airport is not sufficient. If only wind information on west to east-northeast direction
is needed, the wind information of the airport should be used because it will give a good impression on wind directions and velocities at the Peninsula de Hicacos.

### 3.6.4 Tropical Cyclones and cold fronts

Cuba lies in the Hurricane Belt, and from September till November is the Hurricane season. Nevertheless, hurricanes have hit Cuba in other months too. Over the past 127 years, the number of hurricanes in the Hurricane Belt has been recorded. See Table 3-6.

<table>
<thead>
<tr>
<th>Period</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>1886-2003</td>
<td>0.5</td>
<td>0.7</td>
<td>2.1</td>
<td>2.9</td>
<td>1.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>

**Table 3-6 Mean number of hurricanes during the last 127 years**

Of course, not every hurricane hits Cuba: most hurricanes go past the island without influencing the weather. Nevertheless, some hurricanes go straight over the island, causing lots of damage and casualties. See Figure 3-23 for the paths the hurricanes and tropical storms followed in 2002, for example.

![Figure 3-23 Paths of hurricanes in 2002 (source: Instituto Metereologia, INSMET)](image)

Cuba had been struck hard by hurricanes and tropical lows in the past. In 1993, a hurricane caused 1 billion dollars of damage and destroyed or damaged about 40,000 homes.
The most significant flooding is produced by tropical hurricanes, cold fronts and the strong winds caused by tropical lows. These phenomena generate the strongest winds in the coastal regions and cause the biggest alterations of the sea level in the Cuban coasts.

Based on wind velocities, there is a distinction made between hurricanes, storms and depressions influencing the Cuban weather. See Table 3-7 and Figures 3-24 and 3-25

<table>
<thead>
<tr>
<th>Classification</th>
<th>Wind velocity (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical depression</td>
<td>&lt; 63</td>
</tr>
<tr>
<td>Tropical storm</td>
<td>63 - 117</td>
</tr>
<tr>
<td>Tropical Hurricane</td>
<td>&gt; 117</td>
</tr>
</tbody>
</table>

Table 3-7 Classification of Tropical cyclones

Figure 3-24 Hurricane Michelle (source: INSMET)

Figure 3-25 Tropical storm Chantal (source: INSMET)

3.6.5 Tropical hurricanes

Tropical hurricanes originate from the Atlantic Ocean between 5° and 35° latitude and are defined as centers of low pressure zones. During their lifetime, their diameter can grow from 150 to 1000km. Tropical hurricanes causes extreme winds, inundation by intensive rainfall and huge swell and water level set up.
During hurricanes, air pressure may fall to a very low level. In deep water, this results in a rise of sea level of about 1cm per hPa for pressures under the normal 1013hPa. For example, when Hurricane Lily struck Cuba in 2002 the air pressure fell to 938hPa, resulting in a sea level rise of about 65cm. The lowest pressure ever was measured during hurricane Gilbert in 1988, when air pressure fell to 888hPa.

The lowest pressure is measured in the center of the hurricane, where wind velocities are not as high as in the rest of the hurricane. Therefore, in the center wave action is not as high as in the rest of the hurricane. On the location of the biggest wave action, sea level rise is about a third of the rise in the center.

Hurricanes are classified by the scale of Saffir-Simpson. See Table 3-8.

<table>
<thead>
<tr>
<th>Category (Saffir-Simpson)</th>
<th>Pressure in the center (hPa)</th>
<th>Max. wind velocity (km/h)</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&gt; 980</td>
<td>118 - 153</td>
<td>Small</td>
</tr>
<tr>
<td>2</td>
<td>979 - 965</td>
<td>154 - 177</td>
<td>Moderate</td>
</tr>
<tr>
<td>3</td>
<td>964 - 945</td>
<td>178 - 209</td>
<td>Extensive</td>
</tr>
<tr>
<td>4</td>
<td>944 - 920</td>
<td>210 - 250</td>
<td>Extreme</td>
</tr>
<tr>
<td>5</td>
<td>&lt; 920</td>
<td>&gt; 250</td>
<td>Catastrophic</td>
</tr>
</tbody>
</table>

Table 3-8 Classification of Hurricanes by Saffir-Simpson

The exact causes of tropical hurricanes is not determined yet, but there are a three basic principle conditions necessary: the presence of a initial disturbance (for example an cold front), the temperature of the upper layer of sea water had to be above 26.5°C and the Coriolis parameter had to be dissimilar to zero.

In October 1996, lots of damage was done to constructions on the beach of Varadero when it was struck by the hurricanes Joseph and Lily.

3.6.6 Cold fronts

A cold front is a surface which separates a mass of cold and dry air at high altitude from a mass of hot and humid air of lower altitudes.

The cold fronts that strike Cuba are characterized by a mass of dry continental air causing winds from the north which can be very strong (occasionally reaching hurricane force) and accompanied by rainfall and heavy sea. The biggest waves are
generated by the winds from the northwest, because from this direction the wind has the longest fetch. The cold fronts appear in the months October until April although they have been registered in September and May as well.

By the Institute of Meteorology (INSMET), the following classification of cold fronts is made:

Classical cold fronts:  
Classical cold fronts are associated with tropical lows that move in the Gulf of Mexico or territories adjacent to the United States. First they produce southern winds, but when the low centre moves closer to Cuba the direction of wind changes from south to west to northwest. Along with this change in direction, the wind velocity increases.

Secondary fronts:  
Secondary fronts strike Cuba one or two days after a classical front. They maintain the previous barometrical system but with a certain discontinuity in the meteorological elements.

Revisiones fronts:  
Revisiones fronts produce a backward motion of wind in eastern to northeastern to northern direction with increasing cloudiness, rainfall and temperature fall.

The wind velocities that are caused by cold fronts are classified as in Table 3-8.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Maximum wind velocity (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak</td>
<td>&lt; 36</td>
</tr>
<tr>
<td>Moderate</td>
<td>37 - 119</td>
</tr>
<tr>
<td>Strong</td>
<td>&gt; 120</td>
</tr>
</tbody>
</table>

Table 3-9 Classification of cold fronts

The classical fronts are by far the most dominating cold fronts with a moderate force (84%).

Though they produce lesser wind velocities and therefore lesser wave heights, in Cuba most economic damage is caused by the cold fronts because they occur more frequently than tropical hurricanes.
3.6.7 Climate change

Due to the so called greenhouse effect, global temperature is rising. This rise in temperature causes melting of the ice caps on the poles, resulting in a global sea level rise. This results in a net subsidence of the coasts of Cuba.

In Varadero, a net sea level rise of 1.9 mm/year has been measured by the Institute of Oceanology. A group of specialists of this institute also calculated the estimated sea level rise in Cuba for the next century: 2.9 mm/year. This corresponds to calculations the United States have made for the Gulf of Mexico.

3.6.8 Summary

There is little variance in temperature in Varadero, and the temperature normally is in between 19 °C and 32 °C. Sea water temperature is between 26 °C and 32 °C. Annual rainfall is 1320 mm, though there are significant differences throughout the country. This rain falls in 85 to 100 days a year and two third of the rain falls during the Wet Season that lasts from May until November.

Wind is most of the times blowing from the east in Cuba. Wind velocities and directions obtained from the global wave statistics should only be used when wind information given by the airport of Varadero is not sufficient.

Based on wind velocities, a distinction can be made between tropical depressions, storms and hurricanes. During hurricanes, wind velocity exceeds 117 km/h. Tropical storms occur more often than hurricanes.

Cuba lies within the Hurricane Belt, and from August to November runs the Hurricane season. Cuba is often struck by hurricanes, resulting in a lot of damage. Hurricanes are classified with the scale of Saffir-Simpson.

The weather in Cuba can be disturbed seriously by cold fronts. There are three types of cold fronts classified by the INSMET. Most common is the classical cold front. The other types are "Secondary front" and "Revisiones front". Based on wind velocities, they can be classified as weak, moderate or strong.

Global sea level is rising due to for example the greenhouse effect, and a mean sea level rise of 1.9 mm/year has been measured at the Peninsula de Hicacos. Estimations by the Oceanographic institute indicate a sea level rising at the peninsula in the next century of 2.9 mm/year.
3.7 Oceanography

3.7.1 Elevations of the sea

Elevations of the sea can be caused by several influences.

Astronomic tide:
- The astronomical tide in the north of Cuba can be described as diurnal with a small tidal difference. Tidal levels are given for the bay of Cardenas these data are derived from the Hydrographical chart of the British Admiralty and are shown in Table 3-10. The reference of this table is MLSL in the port of La Isabela (app. 150 km east of Varadero).

<table>
<thead>
<tr>
<th>Height above datum of soundings (m)</th>
<th>Average heights</th>
<th>Heights at Springs near the Solstices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Place:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean higher</td>
<td>Mean lower</td>
<td>Mean lower</td>
</tr>
<tr>
<td>Mean higher</td>
<td>Mean lower</td>
<td>Mean higher</td>
</tr>
<tr>
<td>Mean lower</td>
<td>Mean lower</td>
<td>Mean lower</td>
</tr>
<tr>
<td>Bay of Cardenas</td>
<td>0.52</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>0.18</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 3-10 Tide levels

From this table Mean Sea Level is derived as the mean between high tide and low tide during spring tide; 0.34 m. Tidal range is approximately 0.20 m.

Atmospheric pressure:
- The highest elevation due to low pressure found at the Cuban coast is measured in 1998 during hurricane Gilbert (1998) an elevation of 1.5 m. is measured.

Wind set up:
- Estimate for the wind set up can be done by the hand of the fetch and velocity of the wind, and the depth of the sea in this fetch. The calculated wind set-up is 0.1 m\(^1\).

\(^1\) Havana City Sea Wall Malecon, Projectgroup CF06 (2003), TUDelft
Wave set up:
- An estimate of the wave set-up can be done with data about among others bathymetry and configuration of the coast. The actual value for the wave set-up is estimated to be 1 m high for the wave of 6 m and 0.8m for the wave of 4.7m²

Wind and wave set up cannot occur at the same time in Cuba. This is because of the fact that the duration of storms and hurricanes at the coast is short. Therefore during storms; wind setup can occur. But when the high swell waves approach the shore, causing wave set-up the storm has past already¹. The highest set-up due to wind and waves at the coast of Varadero is 1.5m and is measured in 2001 during hurricane Michelle.

3.7.2 Currents

Two types of currents can be found near Varadero. These are the currents caused by tide, and residual currents.

Tidal current due to astronomic phenomena:
- The tide at Varadero is diurnal. The main direction of the tidal current is during flood East-Northeast and during ebb the main direction is West-Northwest. The average direction velocity is approximately 10cm/s and the maximum velocity is 37cm/s.

Residual Currents:
- Salinity differences caused by:
  - Temperature differences: Sea water temperature varies from 26°C in winter to 32°C in summer.
  - Salinity differs from 35.4‰ in winter to 35.6‰ in summer.
- Wind driven currents.

Wind driven and tidal currents have an important impact on the coast; these will be taken into account. The currents caused by temperature, density and salinity differences are estimated to have such small velocities that they can be neglected.

¹ Dr. L. Cordova-Lopez
3.7.3 Waves

In order to calculate the influence of the waves and the resulting currents long shore it is necessary to get an idea how big the waves can get, how often they occur and with what period and direction. A division is made between annual waves (statistically determined) and short term effects due to storm surges.

Different sources are used to come to an estimate of the wave conditions. First Cuban sources will be given and analyzed, after this the Global Wave Statistics will be analyzed. In the end of this Paragraph a comparison will be made and conclusions will be drawn.

All data consist a significant wave height \((H_s)\), the value is determined as; the mean height of the one third highest waves.

3.7.3.1 Cuban sources of information

Cuban data of the wave height are given by two institutes, INSMET and the Institution of Oceanology.

In order to obtain this data the meteorological institute reviewed 43 cases of tropical cyclones and 498 cases of cold fronts, which appeared in 75 respectively 22 years. For each case the wind field and the wave parameters were calculated. From these the average wind velocity and the return function of each case were derived and finally a region of extreme values for waves on deep water was drawn up.

Below are the data provided by these two institutes (Table 3-11).
Instituto Meteorologico

Return periods in T years

<table>
<thead>
<tr>
<th>T</th>
<th>$H_s$(m)</th>
<th>T(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5.0</td>
<td>9.0</td>
</tr>
<tr>
<td>5</td>
<td>6.0</td>
<td>10.0</td>
</tr>
<tr>
<td>10</td>
<td>7.95</td>
<td>10.57</td>
</tr>
<tr>
<td>20</td>
<td>9.06</td>
<td>10.98</td>
</tr>
<tr>
<td>50</td>
<td>10.34</td>
<td>11.04</td>
</tr>
<tr>
<td>75</td>
<td>11.61</td>
<td>11.45</td>
</tr>
<tr>
<td>100</td>
<td>11.93</td>
<td>11.55</td>
</tr>
<tr>
<td>200</td>
<td>13.83</td>
<td>11.75</td>
</tr>
</tbody>
</table>

$H_s =$ Significant wave height in meters
T= Wave period in seconds

Institute of Oceanology

Return periods in T years for the Havana sea coast for a storm of 3 hours

<table>
<thead>
<tr>
<th>T</th>
<th>$H_s$(m)</th>
<th>T(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.18</td>
<td>6.6</td>
</tr>
<tr>
<td>10</td>
<td>3.64</td>
<td>6.9</td>
</tr>
<tr>
<td>20</td>
<td>4.08</td>
<td>7.3</td>
</tr>
<tr>
<td>25</td>
<td>4.22</td>
<td>7.4</td>
</tr>
<tr>
<td>50</td>
<td>4.68</td>
<td>7.7</td>
</tr>
<tr>
<td>100</td>
<td>5.16</td>
<td>8.0</td>
</tr>
<tr>
<td>200</td>
<td>5.62</td>
<td>8.3</td>
</tr>
<tr>
<td>500</td>
<td>6.27</td>
<td>8.6</td>
</tr>
<tr>
<td>1000</td>
<td>6.76</td>
<td>8.9</td>
</tr>
</tbody>
</table>

Table 3-11 Data of Cuban institutes

The data from the Institute of Oceanology indicate only the significant wave heights for a storm of 3 hours. Data of wave directions are not available.

As is clearly visible in the data above, these data can be used to make an estimate of the $H_s$ and T, if we assume a return period of a normative wave for the Varadero situation.

It is also clear that the data provide a significant wave height not for a one year period, but the highest significant wave height which is possible to occur within the return period. Therefore no annual, but only extreme situations are within these data.

3.7.3.2 Analyses of Cuban wave information

As is shown from the data in Table 3-11 there are differences between the data of these two sources.

The data from the Institute of Oceanology indicate the significant wave heights measured during a storm of 3 hours.
The data of INSMET and the Institute of Oceanology lack information about wave directions therefore are difficult for interpretation and application for the investigation of sediment transport.

### 3.7.3.3 Global Wave Statistics

Another source of information about the wave climate can be obtained from the Global Wave Statistics (GWS). In order to determine the deep water wave climate numerous ship observations have been used.

Global Wave Statistics divides the most important seas and oceans into areas where the wave climate is more or less similar. For each area the conditions are given for 4 periods per year. For every period there are data of significant wave height and period from eight directions. Each direction contains the chance of occurrence for the significant wave heights and its corresponding periods.

According to Global Wave Statistics the Hicacos Peninsula is almost located on the border of two areas: area 32 and 33)

![Area Map](image)

Area 32 describes the wave climate for the entire Gulf of Mexico including the southern coast of America towards Florida, the entire coast of Mexico and the western coasts of Cuba. Area 33 describes the wave climate on the eastern shore of Florida, the coasts of the Bahamas and the northern shores of Cuba, Haiti and the Dominican Republic. Areas 32 and 33 have as border the 81° West longitude. This is only 15 kilometer east of the eastern point of the Hicacos Peninsula. Although the wave climate in these two areas does not vary much, a choice has to be made from which area to use the data.
Area, heights, directions, seasons and periods:

The main wave direction is clearly from the eastern directions in both areas but because of the orientation of the coast of the peninsula (30 degrees with the equator in northeast direction) the waves from east will not have a large impact on the Peninsula. Instead, because of this orientation, the coast will be subject mostly to waves from the directions: West, Northwest, North and Northeast. So from now on, area 32 will be taken as source to calculate the wave conditions at the Peninsula.

Finally only the annual data will be looked at because there is only a small difference between the wave heights and periods over the year. The only phenomena that cause significant higher wave heights and periods are the cold fronts in the winter and the hurricanes in summer and autumn (These effects will be discussed separate below as said). This means that only the annual data of the directions from directions West, Northwest, North and Northeast from area 32, will be taken into account.

<table>
<thead>
<tr>
<th>AREA 32</th>
<th>ANNUAL</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>NORTH</th>
<th>NORTH EAST</th>
</tr>
</thead>
<tbody>
<tr>
<td>PERCENTAGE OF OBS = 9.82%</td>
<td>PERCENTAGE OF OBS = 18.19%</td>
</tr>
<tr>
<td>ZERO CROSSING PERIOD (s)</td>
<td>ZERO CROSSING PERIOD (s)</td>
</tr>
<tr>
<td>SIGNIFICANT WAVE HEIGHT</td>
<td>SIGNIFICANT WAVE HEIGHT</td>
</tr>
<tr>
<td>1-4</td>
<td>5-8</td>
</tr>
<tr>
<td>TOTAL 97 308 340 180 59 14 3 1</td>
<td>TOTAL 188 341 319 140 44 11 4 1</td>
</tr>
<tr>
<td>1-4</td>
<td>5-8</td>
</tr>
<tr>
<td>2-3</td>
<td>4-7</td>
</tr>
<tr>
<td>TOTAL 71 144 82 27 5</td>
<td>TOTAL 28 161 80 25 4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WEST</th>
<th>NORTH WEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>PERCENTAGE OF OBS = 3.29%</td>
<td>PERCENTAGE OF OBS = 4.93%</td>
</tr>
<tr>
<td>ZERO CROSSING PERIOD (s)</td>
<td>ZERO CROSSING PERIOD (s)</td>
</tr>
<tr>
<td>SIGNIFICANT WAVE HEIGHT</td>
<td>SIGNIFICANT WAVE HEIGHT</td>
</tr>
<tr>
<td>1-4</td>
<td>5-8</td>
</tr>
<tr>
<td>TOTAL 271 397 234 70 18 3 1</td>
<td>TOTAL 118 332 332 160 46 11 2</td>
</tr>
<tr>
<td>1-4</td>
<td>5-8</td>
</tr>
<tr>
<td>2-3</td>
<td>4-7</td>
</tr>
<tr>
<td>TOTAL 51 102 87 27 5</td>
<td>TOTAL 84 161 80 25 4</td>
</tr>
</tbody>
</table>

Figure 3-26 the main directions and the histogram with wave conditions
Weighted averaged wave period can be used for the calculation of sediment transport. This will be done for these four directions. The mean period is determined by the main point of the histogram which can be determined by multiplying the period by the percentage of the total appearance (for the value of the period <4 a value of 3 is assumed). All these numbers are added and divided by the total number. This way the weighted mean period is obtained. A mean height can be required, this can be calculated to multiply the probability of occurrence of a wave for every height (right column) with its height.

The weighted mean $H_s$ for every direction is given in Table 3-12

<table>
<thead>
<tr>
<th>Direction</th>
<th>Mean significant wave height, $H_s$ (m)</th>
<th>Mean period, $T$ (s)</th>
<th>Percentage of observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>North East</td>
<td>1.51</td>
<td>5.10</td>
<td>18.19%</td>
</tr>
<tr>
<td>North</td>
<td>1.71</td>
<td>5.32</td>
<td>9.82%</td>
</tr>
<tr>
<td>North West</td>
<td>1.74</td>
<td>5.19</td>
<td>4.93%</td>
</tr>
<tr>
<td>West</td>
<td>1.33</td>
<td>4.60</td>
<td>3.29%</td>
</tr>
</tbody>
</table>

Table 3-12 Data from GWS

3.7.3.4 Analyses of the Global Wave Statistics

- Over 100,000 measurements in this area have been done; therefore the accuracy will be accepted.
- Global wave statistics can be used to find wave height, periods and directions.
- The measurements of the GWS show a maximum significant wave height of 7-8 meters.
- The data from the GWS include conditions during hurricanes and cold fronts (this proof will be given separate below in the short term phenomena).

3.7.3.5 Short term phenomena

Due to tropical storms (and worse: hurricanes) in the hurricane season and the cold fronts in the winter much higher waves are generated due to the much higher wind velocities than usual during the year at Cuba. Because of the high waves these phenomena can cause large sediment transport in the surf zone although their frequencies are low.
Hurricanes

The Cuban climate knows a hurricane season from September until November as described earlier. During the passage of a hurricane very large wave heights and periods can occur. There are recordings over many years of hurricanes and of their wind velocities (Table 3-13).

<table>
<thead>
<tr>
<th>No.</th>
<th>Meteorological phenomenon</th>
<th>Date</th>
<th>Significant wave height</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>hurricane Eloise</td>
<td>23-sep-1975</td>
<td>5.4</td>
<td>strong</td>
</tr>
<tr>
<td>2</td>
<td>strong cold front</td>
<td>19-jan-1977</td>
<td>5.5</td>
<td>strong</td>
</tr>
<tr>
<td>3</td>
<td>strong cold front</td>
<td>2-nt-1980</td>
<td>4.2</td>
<td>moderate</td>
</tr>
<tr>
<td>4</td>
<td>strong cold front</td>
<td>5-nov-1982</td>
<td>2.5</td>
<td>weak</td>
</tr>
<tr>
<td>5</td>
<td>moderate cold front</td>
<td>17-mrt-1983</td>
<td>5.6</td>
<td>strong</td>
</tr>
<tr>
<td>6</td>
<td>tropical low</td>
<td>28-feb-1984</td>
<td>4.3</td>
<td>moderate</td>
</tr>
<tr>
<td>7</td>
<td>moderate cold front</td>
<td>29-mrt-1984</td>
<td>3.6</td>
<td>weak</td>
</tr>
<tr>
<td>8</td>
<td>moderate cold front</td>
<td>23-nov-1984</td>
<td>3.1</td>
<td>weak</td>
</tr>
<tr>
<td>9</td>
<td>moderate cold front</td>
<td>4-jan-1985</td>
<td>3.7</td>
<td>weak</td>
</tr>
<tr>
<td>10</td>
<td>moderate cold front</td>
<td>12-feb-1985</td>
<td>3.4</td>
<td>weak</td>
</tr>
<tr>
<td>11</td>
<td>hurricane Juan</td>
<td>28-okt-1985</td>
<td>5.8</td>
<td>strong</td>
</tr>
<tr>
<td>12</td>
<td>hurricane Kate</td>
<td>19-nov-1985</td>
<td>5.0</td>
<td>moderate</td>
</tr>
<tr>
<td>13</td>
<td>tropical low</td>
<td>6-jun-1987</td>
<td>6.1</td>
<td>strong</td>
</tr>
<tr>
<td>14</td>
<td>moderate cold front</td>
<td>23-jan-1987</td>
<td>3.9</td>
<td>weak</td>
</tr>
<tr>
<td>15</td>
<td>hurricane Floyd</td>
<td>12-oct-1987</td>
<td>5.2</td>
<td>strong</td>
</tr>
<tr>
<td>16</td>
<td>moderate cold front</td>
<td>26-jan-1987</td>
<td>3.5</td>
<td>weak</td>
</tr>
<tr>
<td>17</td>
<td>tropical low</td>
<td>12-apr-1988</td>
<td>4.5</td>
<td>moderate</td>
</tr>
<tr>
<td>18</td>
<td>moderate cold front</td>
<td>15-feb-1991</td>
<td>4.0</td>
<td>weak</td>
</tr>
<tr>
<td>19</td>
<td>tropical low</td>
<td>6-mrt-1992</td>
<td>5.3</td>
<td>strong</td>
</tr>
<tr>
<td>20</td>
<td>tropical low</td>
<td>13-mrt-1993</td>
<td>5.3</td>
<td>strong</td>
</tr>
<tr>
<td>21</td>
<td>tropical low</td>
<td>3-mrt-1994</td>
<td>4.6</td>
<td>weak</td>
</tr>
<tr>
<td>22</td>
<td>tropical storm Gordon</td>
<td>14-nov-1994</td>
<td>4.0</td>
<td>weak</td>
</tr>
<tr>
<td>23</td>
<td>tropical low</td>
<td>23-dec-1994</td>
<td>3.0</td>
<td>weak</td>
</tr>
<tr>
<td>24</td>
<td>hurricane Opal</td>
<td>4-okt-1995</td>
<td>3.2</td>
<td>weak</td>
</tr>
<tr>
<td>25</td>
<td>strong cold front</td>
<td>9-jan-1996</td>
<td>3.4</td>
<td>weak</td>
</tr>
<tr>
<td>26</td>
<td>moderate cold front</td>
<td>4-feb-1996</td>
<td>3.6</td>
<td>weak</td>
</tr>
<tr>
<td>27</td>
<td>strong cold front</td>
<td>8-mrt-1996</td>
<td>3.8</td>
<td>weak</td>
</tr>
<tr>
<td>28</td>
<td>moderate cold front</td>
<td>20-mrt-1996</td>
<td>2.6</td>
<td>weak</td>
</tr>
<tr>
<td>29</td>
<td>moderate cold front</td>
<td>14-dec-1997</td>
<td>3.8</td>
<td>weak</td>
</tr>
<tr>
<td>30</td>
<td>strong cold front</td>
<td>27-dec-1997</td>
<td>3.2</td>
<td>weak</td>
</tr>
<tr>
<td>31</td>
<td>tropical low</td>
<td>4-feb-1998</td>
<td>4.7</td>
<td>moderate</td>
</tr>
<tr>
<td>32</td>
<td>hurricane Georges</td>
<td>25-sep-1998</td>
<td>4.0</td>
<td>weak</td>
</tr>
<tr>
<td>33</td>
<td>hurricane Irene</td>
<td>15-okt-1998</td>
<td>4.0</td>
<td>weak</td>
</tr>
<tr>
<td>34</td>
<td>hurricane Michelle</td>
<td>11-nov-2001</td>
<td>7.6</td>
<td>moderate</td>
</tr>
</tbody>
</table>

Table 3-13 Meteorological phenomena near Varadero

When looking at these data it is seen that the maximum significant wave height ever recorded was during hurricane Michelle. When also the data from GWS are considered it can be that the maximum significant wave height is equal to 7-8 meters. This means that the waves due to hurricane and cold fronts already are in GWS data.

This also implies that using the data from GWS is sufficient. The same goes for the data found from the INSMET data. A significant wave height of 7,95m for a return period of ten years is found.
3.7.3.6 Evaluation and conclusions

The information of Cuban institutes give information on significant wave height, period and return period, but lack information about wave directions therefore are difficult for interpretation and apply for the investigation of sediment transport.

Global wave statistics can be used the find wave height, periods and directions. The data from the GWS include conditions during hurricanes and cold fronts. The use of the data from GWS is sufficient for the calculation of sediment transport.

3.7.4 Summary

Elevations of the sea
An elevation of the sea or due to several effects, the tide is a deterministic value. Values are derived from the nautical map of the British Admiralty, MSL is 0.34 m above MLSL. Tidal range is approximately 0.20 m. Other elevations are due to; atmospheric pressure, wind set-up and wave set-up.

Currents
Two types of currents can be found near Varadero. These are tide currents, and residual currents. The velocity of tidal current can vary between 10 cm/s and 37 cm/s. From the residual currents; only the wind driven current is taken into account.

Waves
Cuban institutes provide information on significant wave height, period and return period, but lack information about wave directions. Therefore they are difficult for interpretation and apply for the investigation of sediment transport.

Global wave statistics can be used the find wave height, periods and directions. The data from the GWS include conditions during hurricanes and cold fronts. The use of the data from GWS is sufficient for the calculation of sediment transport.

From Global Wave Statistics the following data are derived (Table 3-14).

<table>
<thead>
<tr>
<th>Direction</th>
<th>Averaged significant wave height, $H_s$ (m)</th>
<th>Averaged period, $T$ (s)</th>
<th>Percentage of observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>1.71</td>
<td>5.32</td>
<td>9.82 %</td>
</tr>
<tr>
<td>North east</td>
<td>1.51</td>
<td>5.10</td>
<td>18.19 %</td>
</tr>
<tr>
<td>North West</td>
<td>1.74</td>
<td>5.19</td>
<td>4.93 %</td>
</tr>
<tr>
<td>West</td>
<td>1.33</td>
<td>4.60</td>
<td>3.29 %</td>
</tr>
</tbody>
</table>

Table 3-14 Data from Global Wave Statistics
3.8 Organization structure of the Varadero coastal zone

The peninsula of Varadero is the property of the state of Cuba. It has become a very large income generator through tourism. The main uses of the peninsula of Hicacos are:

Tourism
- The main reason to spend a vacation in Varadero is for the sun and the beach. This resulted in the building of hotels, resorts, and infrastructure. Also many tourist facilities have been constructed in order to entertain visitors, such as bars, restaurants, and sport facilities. Approximately 1.4 million people visit the peninsula every year.

Residential
- Historic Varadero has approximately 20,000 inhabitants, mainly working in the tourist sector.

Environmental
- Parts of the peninsula feature unique dune vegetation as well as marine life.

This very intensive use of the coastal zone combined with structural erosion demands a well organized system. The Cuban authorities are responsible to achieve this optimal use of all different functions, because they own the beach. Different organizations are involved in the system of maintenance and improvement of the beach of Varadero. These organizations are:

- Ministry of Science, Technology and Environment (CITMA).
- Ministry of Tourism.
- ALMEST.
- Department of Coastal Processes at the Institute of Oceanology. (IO)
- Institute of Recuperation of the beach of Varadero. (ORPV)
- Centre of Environmental Services of Matanzas. (CISAM)

The activities and goals of each organization are described separately in the following Paragraphs. Paragraph 3.9.4 gives a relation diagram and money flow diagram between the organizations.
3.8.1 ALMEST

Goals: Look after the interest of hotels and resorts in Cuba (more specific in Varadero) and the development of tourism on the peninsula.

Function: Hotels at Varadero are united in this organization. All hotels in Varadero are for one part owned by the Cuban authorities, the other part is owned by foreign parties from i.e. Germany, Spain, Mexico and Italy.

Area: All hotels in Cuba.

Structure: Part of the Ministry of Tourism.

3.8.2 Department of Coastal Processes at the Institute of Oceanology

Departamento de Procesos Costeros del Instituto de Oceanología (IO).


Function: Received in 1997 a contract from the Ministry of Science, Technology and Environment to investigate possible engineering solutions for the erosion problems of the peninsula. This contract included a monitor program in section 1 from 1998 (before the nourishment until 2002). The institute received a contract to do all research for nourishment in section 3.

Area: All beaches and coastal zones in Cuba. But this institute is especially involved in all research regarding the erosion in Varadero.

Work Area: All research regarding nourishment in Varadero.

Structure: Part of the Ministry of Science Technology and Environment.
3.8.3 Institute of recuperation of the beach of Varadero

Oficina por la recuperacion de la playa de Varadero (ORPV).

Goals: Protection and maintenance of the coastal zone of Varadero. Most important goal is to acquire equilibrium between the recreational use of the beach, and his natural dynamic system.

Function: Founded in 1996 to act as an intermediate between the government and the companies that do the maintenance and nourishment work on the peninsula. Function is to divide funding between the principal (CITMA), and the executors of maintenance- and nourishment projects. The organization is responsible for the maintenance of the beach on the peninsula.

Area: The area of the institute is the coastal zone limit, which is defined in Appendix 5. Annual maintenance is done in the critical zones (chapter 3.1.4).

Work area: Several maintenance projects in the Varadero coast.

Structure: Part of the ministry of Science, Technology and Environment (CITMA). The institute receives indirect funding from the ALMEST organization (The organization in which the hotels are united). Works close with Centro de Servicios Ambientales Matanzas (CISAM).

Structure: Part of the Ministry of Science Technology and Environment. It has a close relation with the Centre of Environmental services of Matanzas.

3.8.4 Centre of Environmental Services of Matanzas

Centro de Servicios Ambientales Matanzas (CISAM).

Goals: Investigation of the environmental effects of hotels and industries on Varadero.

Function: Intermediate for hotels and organizations who implement environmental solutions. This organization makes the environment investigations on the peninsula and makes proposals to hotels. The
hotels will decide which investigation will be executed and will be useful to improve the environmental conditions on the peninsula.

Area: The area of investigation of this organization is the total area of the peninsula of Varadero from the toe of the dune land inward. This area excludes the beach.

Work Area: Water on island, quality and quantity of vegetation, biodiversity, pollution, air pollution, granulation and origin of the sands, supervising of protected area at the north end of the peninsula.

Structure: Part of the Ministry of Science, Technology and Environment. The institute receives funding from ALMEST (the organization in which the hotels are united). It works close with ORPV. The northeast point of Varadero is appointed by the U.N. as protected; therefore it receives funding from the U.N. (Global Environment Funding).

3.8.5 Management structure of the peninsula

The Ministry of Science, Technology and Environment (CITMA) works very close with the Ministry of Tourism. The last acts as indicator of problems or demands, in the name of the hotel owners united in the organization Called ALMEST, while ORPV manages the research and carrying out of technical solutions and maintenance.

The ministry CITMA manages three organizations involved in the maintenance and protection of the coastal zone. Technical research and solutions are done by the Institute of Oceanology. The maintenance of the beaches is done by the office of recuperation of the beach of Varadero (ORPV). Environmental research is carried out by the Centre of environmental services of Matanzas. (CISAM)

This can be schematized in the following structure diagram (Figure 3-27).
Figure 3-27 Organization diagram of Varadero

The money funding flow comes from two sides. The first flow of money comes from the state in the form of contribution for the Ministries (in other words: the Cuban taxpayer pays). The second flow comes from the hotels and resorts that pay contribution to ALMEST. ALMEST pays taxes and contribution to the Cuban ministry of tourism. In order to pay for the actual research and solutions the ministry of tourism gives funding to the ministry CITMA. This ministry divides the money according to the costs that each organization makes. The executing parties are paid by the ORPV.

The money flows are schematized in the following diagram (Figure 3-28).

Figure 3-28 Money flow in Varadero
3.8.6 Summary

The main uses of the peninsula are tourism, residential and environmental. In order to obtain an optimal use of the area, different parties are involved, these are:

- Ministry of Science, Technology and Environment (CITMA).
- Ministry of Tourism.
- ALMEST.
- Department of Coastal Processes at the Institute of Oceanology. (IO)
- Institute of Recuperation of the beach of Varadero. (ORPV)
- Centre of Environmental Services of Matanzas. (CISAM)

The relation between these organizations is that the ministry CITMA manages three organizations involved in the maintenance and protection of the coastal zone. Technical research and solutions is done by the Institute of Oceanology. The maintenance of the beaches is done by the office of recuperation of the beach of Varadero (ORPV). Environmental research is carried out by the Centre of environmental services of Matanzas (CISAM). A large part of the money in order to pay for the different means of beach protection, maintenance and recovery comes from the ministry of Tourism. The hotels at Varadero are united in an organization called ALMEST.
3.9 Costs of materials and equipment available in Cuba

There is a difference between cost estimation in Cuba and cost estimation in The Netherlands. Therefore some research was done about cost estimation in Cuba.

3.9.1 PRECONS: Construction cost estimation in Cuba

In Cuba the PRECONS\(^1\) catalogue is used to estimate construction costs. The principles established in the catalogue are the basis of official and mandatory documents for the cost estimation and certification of construction of new works, reparation, maintenance and restorations of monuments.

The PRECONS catalogue gives the following procedure to calculate construction costs represented in Table 3-15.

<table>
<thead>
<tr>
<th>PRIMARY COSTS</th>
<th>Elements, components and their formulation</th>
<th>Equivalence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>Definition</td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>Direct costs material</td>
<td>C1</td>
</tr>
<tr>
<td>C2</td>
<td>Direct costs of labor</td>
<td>C2</td>
</tr>
<tr>
<td>C3</td>
<td>Direct costs of equipment</td>
<td>C3</td>
</tr>
<tr>
<td>C4</td>
<td>Direct costs of means of support</td>
<td>3% of C1+C2+C3</td>
</tr>
<tr>
<td></td>
<td>and small material</td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>Total direct costs</td>
<td>C1+C2+C3+C4</td>
</tr>
<tr>
<td>C6</td>
<td>Indirect costs</td>
<td>29% of C5</td>
</tr>
<tr>
<td>C7</td>
<td>Total costs</td>
<td>C5+C6</td>
</tr>
<tr>
<td>C8</td>
<td>Profit</td>
<td>20% of the Elaboration costs*</td>
</tr>
<tr>
<td>C9</td>
<td>Total Primary Costs</td>
<td>C7+C8</td>
</tr>
</tbody>
</table>

\(^1\) PRECONS sistema de precios de la construcción tomo1
Elaborated by: Dirección de Presupuestos y Precios del Ministerio de la Construcción Empresa de Informática y Automatización de la Construcción (ICON), La Habana 1998
SECONDARY COSTS

<table>
<thead>
<tr>
<th>Elements, components and their formulation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 Temporary facilities</td>
<td>P1</td>
</tr>
<tr>
<td>P2 Transport</td>
<td>P2</td>
</tr>
<tr>
<td>P3 Other additional costs</td>
<td>P3</td>
</tr>
<tr>
<td>P4 Banking</td>
<td>P4</td>
</tr>
<tr>
<td>P5 Insurance</td>
<td>P5</td>
</tr>
<tr>
<td>P6 Unexpected costs</td>
<td>P6</td>
</tr>
<tr>
<td>P7 Total Secondary Costs</td>
<td>P1+P2+P3+P4+P5+P6</td>
</tr>
<tr>
<td>T Total costs of the construction</td>
<td>C9+P7</td>
</tr>
</tbody>
</table>

*Elaboration costs: C2+C3+0.03(C2+C3)+0.2987(C2+C3)=1.3287(C2+C3)

Table 3-15 Cost estimation according to PRECONS, Anexo No. 3

The procedure is classified into two categories: primary costs and secondary costs. The primary costs are the costs that are in a direct relation to the construction to be built. The secondary costs have an indirect relation.

Primary Costs

Direct costs of material (C1)
- Construction material, which forms an integral part of the structure (sand, rock, geotextile etc.)
- Supporting materials, which are used during the work (wood, molds etc.).
- Semi-manufactured parts (the elements that arrive at the construction site in a partial state).
- Prefabricated materials (structures of concrete, structure of wood)
- Costs of the use of water during the fabrication of concrete.

Direct costs of labor (C2)
- Design
- Technical preparations (office, calculations, communication).
- Salaries
- Water and food

Direct costs of equipment (C3)
- Rent of equipment
- Fuel, lubricant (oil), electrical energy.
- Security for the material and equipment
Depreciation and interest
- Maintenance and repair
- Insurance

Direct costs of means of support and small material (C4)

**Secondary Costs**

Temporary facilities (P1)
- Toilets, material warehouses, etc.

Transport (P2)
- Tug boat costs
- Barge costs
- Cargo costs

Other additional costs (P3)
- Removal of unused materials at the completion of the work.

Banking (P4)
- Risks by making an estimation of costs.
- Risks by making an estimation for the time needed for the project.
- Risks of price-changes during the project.

Insurance (P5)

Unexpected costs (P6)
3.9.2 Cost estimation for soft and hard solutions

As mentioned previously in the problem description of this report, hard solutions (i.e. groins or seawall) as well as soft solutions (i.e. beach nourishment once in several years) will be taken into account when considering solution alternatives.

Hard and soft solutions differ from each other in design, materials used and execution. That is why in the estimation of the costs a distinction is made in:

- Cost estimation soft solution
- Cost estimation hard solution

For the estimation of a the costs of a soft solution a reference to the nourishment executed in 1998 by Blankenvoort on the beach of Varadero can be made. The project consisted of nourishing 1 087 835m³ of sand at a cost of 5 million US dollar. This gives a reference value of 4.6 US dollar/m³.

3.9.3 Equipment available in Cuba

In Cuba the most likely company to carry out coastal engineering works would be Empresa de Construcciones Maritimas. Yet foreign contractors cannot be excluded, as was the case in the nourishment of 1998 when Dutch dredging company Blankenvoort carried out the project. In coastal engineering works in the past it has also been the case that only the equipment was hired from abroad but an all-Cuban crew was put on board to execute the work.

3.9.4 Summary

In Cuba the PRECONS catalogue is used to estimate construction costs. According to the procedure in the PRECON, two tables are presented where the cost per unit of different items are represented. This is done for a hard type solution and one for soft type. For the soft type solution a reference of can be taken of 4.6 US dollar/m³. The most likely company to carry out coastal engineering works would be Empresa de Construcciones Maritimas, but participation of foreign companies cannot be excluded.
3.10 Coastal Zone Legislation in Cuba

The legislation regarding the coastal zone in Cuba is regulated in the Decreto Ley para la protección de la Zona Costera (Decree on coastal zone protection). In Article 3 of this decree the types of coasts are defined according to their structure, configuration and extension. The limits of the Coastal zone land inwards are also established in this Article.

The 4 types of coasts are defined as:

- Low terrace
- Rocky cliffs
- Beaches
- Mangrove

Where these coasts can be found on the peninsula is shown in Figure 3-29.

![Figure 3-29 Classification of the coasts of Varadero according to the Decreto-Ley para la protección de la Zona Costera](image_url)

Specification on the coastal zone limits of the different type of coasts is given in Appendix 5.
3.10.1 Summary

The legislation regarding the coastal zone in Cuba is regulated in the Decreto Ley para la protección de la Zona Costera. The coast is classified in four types: low terrace, rocky cliffs, beaches and mangroves. In Appendix 5 coastal zone limits are given.
4 Determination of the causes of erosion

On the Peninsula de Hicacos, the beaches have been monitored by the Institute of Oceanology in the past 30 years. Without any doubt, an erosion trend of the beaches has been observed, see Figure 4-1.

Several studies have been carried out to find the possible causes of this erosion, with different results. In this chapter, a new research will be executed to determine the possible cause(s) of the erosion of the peninsula.

Figure 4-1 Erosion trend observed by Institute of Oceanology
4.1 Introduction

A littoral cell is defined as a stretch of shoreline in which all sediment transport processes are related. In theory, it has zero longshore sediment flow past its updrift and downdrift boundaries. It may contain several sources and sinks.

![Littoral cell diagram]

Figure 4-2 Littoral cell

In Figure 4-2, an example of such a littoral cell is given. Local offshore conditions may cause the local potential sediment transport rate to be less than the overall actual sediment transport, causing accumulation and the forming of beaches in the cell. When conditions remain favorable for beach formation, the beach will continue to increase in size along the littoral cell. When local conditions become unfavorable to beach formation, local sediment outflow rate will be increased locally and there will be loss of beaches.

The Peninsula de Hicacos is no theoretic littoral cell because the input of the system is not zero, and considering the erosion problems the output probably also not. Sources and sinks occur along the coast of the peninsula. Still, the peninsula can be seen as a cell, with a certain amount of input and output.

In this chapter, factors that could influence the source/sink terms and the $Q_{in}$ and the $Q_{out}$ of the cell Peninsula de Hicacos are analyzed. Determined is what factors play a role in the erosion problems on the peninsula, and if this role is a significant one. Five groups of possible causes of the erosion are considered, based in the
distinction of causes of erosion in four groups Bird\footnote{Bird in 1993 distinguished four groups of possible causes for long term erosion: Decrease in sediment supply, Communion, Submergence and Human interference} made in 1993. All possible causes of erosion at the peninsula are divided over these five groups and in the following Paragraphs, for every possible cause will be analyzed if it does or does not play a role in the erosion of the peninsula.

The main groups are:

- Gradients in Sediment Transport
- Changes in the bed material
- Submergence
- Human interference
- Short term erosion

The first three types of erosion are natural causes of erosion that take place over geological time. Only in the last decades have shores become subject to human interference, but it is usually not the only or even the major cause of general beach erosion.

The fifth group (short-term erosion) has been added to include the short-term erosion of Varadero in this research, for example during hurricanes. This is done because short-term erosion can cause severe damage to constructions on and next to the beach.

When something plays a role, it will be analyzed of its’ significance. It is also indicated if it plays a local role or a role in the whole Peninsula.

\section{4.2 Gradients in sediment transport}

Only when gradients in the sediment transport occur, they will result in either sedimentation or erosion. In this Paragraph, gradients in the sediment transport are considered.

\subsection{4.2.1 Cross-shore transport gradients}

The general shape of a coastal profile is the result of a dynamic equilibrium in the cross-shore direction. Such equilibrium can be characterized by its slope. This slope
depends on the wave height, the grain size and the distance from the shore. Thus, the profile changes under influence of changes in these parameters, sometimes giving the impression erosion has occurred. But as theoretically no sand is permanently lost from the cross section, the original condition is theoretically restored by nature in the long run. In practice however, cross-shore transport gradients may occur due to for example the formation of offshore bars, causing losses of sand in the cross section.

It can also occur that storm surges follow each other in so short a period that the beach does not get sufficient time to re-establish. This effect is handled in Paragraph 4.6.2

Cross-shore transport is generally caused by the orbital velocities and, in case of breaking waves, by the undertow. Gravity along the slope also plays a role. Cross-shore transport is often a combination of bottom transport and suspended transport.

Little is known about gradients in cross-shore sand transport. In this research, the assumption is made that there are no cross-shore transport gradients, and that therefore no sand is lost within the cross section due to these gradients.

Sand nevertheless is transported cross-shore in the direction of the sea, mostly during storms. If there is no sufficient beach present after the storm, for example because of the presence of seawalls, this sand will not be brought back.

This effect can occur on the peninsula because on some places there are structures present very close to the sea.

There can be concluded that no sand is lost in cross-shore direction on the Peninsula de Hicacos due to cross-shore gradients, but that the redistribution of the sand due to cross-shore transport can locally cause a retreat of the coastline.

4.2.2 Longshore transport gradients

Longshore transport of sediment is usually caused by the longshore current that is driven by radiation stress of waves approaching under an angle. Sediment transport in itself does not cause any changes in the topography of the coastline, only when there are gradients in the transport rate there will be erosion or sedimentation.

Gradients in the longshore transport can result from (Figure 4-3):
Incident waves under a different angle
Wave height differences along the coast
Bottom material changes
Wind and wave driven currents

Figure 4-3 Causes of gradients in longshore transport (source: Introduction Coastal Engineering, TU Delft)

Concerning picture C in Figure 4-3, the remark is made that an increasing angle of approach only increases sediment transportation when the angle is below 45°.

In the case of the Peninsula de Hicacos, both wave direction and height vary throughout the year, certainly causing longshore transport gradients in time. Because the coast is not fully straight longshore transport gradients can in some places occur.

Wave height differences in deep water along the coast may occur, but those differences will be so small that they are not considered in this research.

Bottom material changes (along the coast) can be of influence as in some sections of the beach the rock terraces underlying the beach are closer to the surface and in some cases even exposed (Figure 4-4). In some parts of the peninsula, there are even no beaches and the coast exists from solid rock.
Figure 4-4 Exposed rock terraces between Calle 23 and 37 (Sept. 2003)

Along the sandy coast of the peninsula, there is variance in mean sand diameter, possibly creating longshore transport gradients. However, the different mean sand diameters are so scattered along the coast that in this research the assumption was made that everywhere on the beaches of the peninsula the sand characteristics are the same.

However, because of the presence of rock at some places along the coast longshore transport gradients due to bottom material changes occur along the coasts of the peninsula. The rock terraces are handled in the Paragraph about the presence of irregularities in the profile.

Wind and wave driven currents play a big role in the longshore transport.

Overall there can be concluded that gradients in longshore transport occur at the Peninsula de Hicacos and they play a significant role in the erosion.

4.2.3  Wind

Along the coast, sediment is transported from the beach by wind, as can be seen in Figure 4-5. Sediment transport by wind plays a dominant role in the formation of dunes, and thus in the shape of the coast immediately landward of the waterline. The amount of sediment that is transported depends among other things on the size of the beach: more sediment will be transported when the beach size is bigger.
Figure 4-5 Sediment transport by wind at Calle 40 (Jan. 2001)

On the Peninsula de Hicacos, strong winds can occur, and most of the time wind is blowing from the same direction. Amounts of sand are blown into but also over the dunes, forming a loss of sediment. Beach size varies over the peninsula, and thus the amount of sediment that is blown away will vary too.

Wind could play a significant role in the erosion of the beaches of the peninsula. In advance, it can not be said whether sediment transport by wind plays a significant role in the erosion, as calculations have to be made.

There will be assumed that sediment transport by wind plays a significant role in the erosion of the peninsula.

4.2.4 Change in the amount of river sediment

A change in a river system will influence the amount of sediment that is transported by a river. By that, it will influence the amount of sediment that eventually may be transported onto the beach.

In the direct neighborhood of the Peninsula de Hicacos, no significant rivers flow into the sea. The nearest rivers that flow into the sea are situated in the bay of Matanzas, about 20 km to the west. Since no sediments of these rivers have been found on the beaches of the peninsula, a change - if any- in the river system of these rivers has not and will not influence the beaches of the peninsula.

Therefore, changes in the amount of river sediment do not play a role in the erosion of Peninsula de Hicacos.
4.2.5 Presence of irregularities on the sea bottom

When irregularities are present at the sea bottom, they may form for example natural breakwaters, disrupting the sediment transport and thus causing erosion and sedimentation in its environment.

In the beach profiles of the Peninsula de Hicacos, there are no noticeable irregularities of the bottom, except from the small rock terraces close to the shore. It is mainly a flat sand bottom with a slight slope ascending from the west to the east.

The small rock terraces will affect the sediment transport because they for example change the wave climate, but it is not likely that it will be a significant effect.

In this research, it will be assumed that the presence of small rock terraces does not influence the sediment transport.

With this assumption, irregularities on the sea bottom do not play a significant role in the erosion of the peninsula.

4.2.6 Currents

Currents in the sea water can influence the amount and direction of sediment transport. All kinds of currents can occur in the water, such as wind driven currents and tidal currents but also density currents. All of these currents can affect the amount of sediment that is transported, for example because they can change the wave climate in the surf zone.

Wind and wave driven currents are handled in 4.2.2.

Because all the other currents, which occur near the Peninsula de Hicacos have small velocities, the effects of these currents can be neglected.

Therefore, the other currents do not play a significant role in the erosion of the peninsula.
4.2.7 Reef sediments

When coral reefs, plants or fish in the sea die, they will perish and the remaining parts will reduce in size and eventually end up as sediment on the sea bottom. This sediment can be transported to the dynamic zone, thus forming an input of sediment. Decrease in the amount of sediment that is produced therefore can form a cause of erosion.

On the beaches of the Peninsula de Hicacos, sediment that originates from coral reefs and plants forms the major part of the composition. Most of the sediment in the bed, approximately 40%, comes from the Algae Halimeda, a sea plant that grows in several fields near the Peninsula.

Therefore, the impact of reef sediments plays a significant role in the erosion of the Peninsula de Hicacos.

4.3 Changes in bed material

When bed material changes, the beach profile will change with it. For example, bigger mean grain sizes will result in a steeper beach and smaller grain sizes can accelerate erosion. In this Paragraph, two possible causes of changes in grain size will be looked at.

4.3.1 Comminution

Beach sediment is not the final size of the material resulting from the hydro-geological process that turns rock into silt and clay. Shingle, cobble and sand are only intermediate steps and the violent coastal climate will continue to decrease the size of the beach materials through a grinding process called comminution. As perfectly stable beach materials are reduced into finer materials, they will no longer be stable as beach building materials and waves will carry the fine sediment into deep water or along the shore to an area with less violent wave action. Wind may also carry it inland. The disappearance of these smaller grain sizes from the active coastal system results in erosion.

On Peninsula de Hicacos, beaches are constantly supplied with new beach sediment by the fields of the Algae Halimeda. The most important field of these Algae, situated
approximately 2 km northeast of the Peninsula, produces new sediment each year. Most of this sediment will reach the beaches of the Peninsula, by that refreshing the existing beach sediment.

Though comminution will occur at the beaches of Peninsula de Hicacos, there is sufficient supply of raw material from the sea. Therefore, comminution will not play a significant role in the erosion of the peninsula.

4.3.2 Qualitative change of river sediments

A change in a river system will influence the characteristics of the sediment that is transported by a river. By that, it will influence the amount and characteristics of sediment that eventually may be transported onto the beach. If sediment size changes, it will influence the beach profile and erosion rate.

As said in 4.2.4, in the direct neighborhood of the Peninsula de Hicacos, no significant rivers flow into the sea. The nearest rivers that flow into the sea are situated in the bay of Matanzas, about 25 km to the west. Since no sediments of these rivers have been found on the beaches of the peninsula, a change – if any- in the river system of these rivers has not and will not influence the beaches of the peninsula. Thereby, it does not play a role in the erosion of Peninsula de Hicacos.

4.4 Submergence

Net coastal submergence (resulting from a relative sinking of the land or a rise in water level) is the result of different mechanisms. Besides global mechanisms, also local phenomena can cause a net coastal submergence.

Human intervention can also cause a net coastal submergence. Human intervention in the coastal zone is handled in the next paragraph.

4.4.1 Global sea level rising

Due to for example the greenhouse effect, global sea level is rising. This process is described in Paragraph 3.6.7 in the subparagraph on climate change. Due to the rise in sea level, wave action near the shore will increase, and erosion takes place.
The Institute of Oceanology has estimated that in the next century net sea level rise on the Peninsula de Hicacos will be 184 mm, or 1.9 mm/year.

The elevation of the mean sea level by global sea rising therefore will have a significant impact on the erosion of the peninsula.

4.4.2 Tectonic activity

When earthquakes occur, they tend to compact the layers of soil in the influenced area. As a result of that, the surface above these layers will subside; wave action near the shore will increase and erosion will take place.

In the area of the Peninsula de Hicacos, no earthquakes are recorded. Therefore, it can be concluded that earthquakes do not play a role in the erosion.

4.4.3 Compaction

If present, compressible sub soils will settle and the land will subside when groundwater level decreases or extra weight is added to the surface. Again, wave action near the shore will increase, and erosion takes place.

On Peninsula de Hicacos there are no compressible sub soils. The layers of soil consist of limestone and sand that is almost incompressible. Therefore, compaction does not play a role in the erosion of the peninsula.

4.5 Human interference

Up till this very day, the coastal zone has provided humans in almost every of their needs, such as drinking water, fertile land, ample resources in terms of game and fish, a sink for the waste products of human society, transport facilities and protection against enemies. Therefore the coastal zone had always been a very attractive zone to live, work and relax.

With the growing of world population, an ever-increasing number of people inhabit the coastal zone, occupying more and more locations that pose serious threats to their inhabitants because of their location close to the water line. Thereby, the dynamic morphological behavior of the coastline is more and more interfered, disturbing the natural dynamics of the coastal zone.
Within the scope of erosion, the impact of human activity on the Peninsula de Hicacos will be analyzed in this paragraph.

4.5.1 **Dune-beach disturbance**

Beach profiles respond to storm-calm cycles by shifting the sand in the cross-shore direction, forming a dynamic equilibrium. For extreme situations, nature provides by stockpiling large quantities of sand in dunes. These dunes are long-term protection against coastal erosion, because they provide adequate elevation of the land contours to prevent flooding and form emergency reservoirs of sand.

During emergencies, like storms and storm surges, sand on the upper beach is moved in offshore direction. This allows the waves to come further into shore and they will attack the toe of the dune, causing them to become unstable and deposit large amounts of sand on the beach, compensating for the sand that has been moved offshore by storm waves. After the storm, the material moved offshore will return onshore, forming expansive dry beaches. Wind will blow back the dry sand inland, replenishing the dunes.

In practice, the situation is more complicated than in theory, due to for example offshore bar formations. But still, it is clear that natural dune beach systems should not be disturbed.

On the Peninsula de Hicacos, many hotels and houses have been constructed within the dune-beach system, disturbing the system seriously. See Figure 4-6.

*Figure 4-6 Hotels and houses within the dune-beach system at Old Varadero (Sept. 2003)*
Most of these hotels and houses were constructed in Old Varadero during the 50's and 60's, when there was no law on the use of the coastal zone. In the 90's, some of the houses were demolished but still about 80 structures are present on the dunes.

Natural vegetation on the dunes was destroyed by commercial activities, thereby disturbing the dune-beach system because wind could freely blow the sand over the dunes into the Peninsula, creating a loss of sediment in the beach-dune system.

The construction of hotels and houses on the dunes and the destruction of natural vegetation on the dunes have disturbed the dune-beach system seriously and play thereby a significant role in the erosion of the peninsula, mainly in the part where Old Varadero is situated but also in the other places where constructions have been built in the dunes.

4.5.2 Lack of a sufficient sewer system

Along with human, structures came to the coastal zone, as told in the previous Paragraph. In first, these structures consisted mainly of houses but along with time roads and other structures were built. Quickly, the coastal zone was occupied by hard structures. In the case of heavy rainfall, these hard structures prevent that rain falls on the soil, thereby accelerating the speed and amount of water that is carried away back to sea.

For the purpose of controlling this increased amount of water, on many places sewers were constructed. On places where there is no sufficient sewer system constructed, water will flow over the streets, looking for the lowest point, often the sea. When the large amount of water finds its way over the beach in small rivers, sediment is transported along with it, flowing into the sea and in this way eroding its path. Along with the water, pollution from the streets is washed away into the sea.

On the Peninsula de Hicacos, heavy rainfall due to hurricanes, cold fronts and storms occurs. In cases of heavy rainfall, the sewer system on the peninsula is not sufficient, and mainly at old Varadero water flows through the streets onto the beach, causing local erosion. See Figure 4-7. Also small amounts of pollution from the street, mainly consisting of oil rests, are washed into the sea.
The effect of the lack of a sufficient sewer system on the total erosion of the Peninsula de Hicacos is small, because not very large amounts of sediment are transported and the effects are temporary, but locally it can play a role.

Therefore, a lack of a sufficient sewer system plays a role in the erosion of the Peninsula de Hicacos, mainly near the part where Old Varadero is situated, but the role can be considered not significant.

4.5.3 Artificial interruption of the longshore transport

When groins or breakwaters are constructed into the sea, they will influence the beach profile and rate of sediment that is transported along the coast because they interrupt the littoral transport. If there is a dominating wave direction, accretion will occur on the up-drift side and erosion will take place on the down-drift side.

On the Peninsula de Hicacos, a few decades ago the Paso Malo breakwater was constructed to protect the channel from silting up. On both side of the channel, the breakwaters have an estimated length of 110 m seawards, highly interrupting the littoral transport. Accretion on the east side of the breakwater and erosion on the west side is clearly visible (see Figure 4-8).
Figure 4-8 Accretion on the east side (left) and erosion on the west side (right) of Paso Malo breakwater (Sept. 2003)

In the background of the right picture, a groin is visible that was constructed by hotel Oasis to protect its beaches from eroding. In Figure 4-9, a better view of this breakwater is given. More to the west, the coast is no longer protected as no tourist facilities are situated there and the coast consists of rocky terraces as far as in the Bay of Matanzas.

Figure 4-9 View on the groin of hotel Oasis (Sept. 2003)

The Paso Malo breakwaters and the two groins of the hotel Oasis are the only breakwaters on or next to the Peninsula de Hicacos. Hereby has to be noted that the most western breakwater at Hotel Oasis is very short, approximately 10 meters.

The littoral transport is interrupted on the peninsula by in total four breakwaters (two at the mouth of the Paso Malo and two in front of Hotel Oasis). In the
neighborhood of these breakwaters, where hotel Oasis is situated, erosion will occur on the downdrift side and therefore they play a significant role in the erosion around them.

4.5.4 Commercial fishing

Most sediment transported to the Peninsula de Hicacos is produced by the fields of Algae Halimeda, northeast of the peninsula. Commercial fishing with nets may cause severe damage to these fields, reducing the total area where the Algae Halimeda grows, resulting in a lower production of sediment each year. When less sediment is transported to the peninsula, it is clear that it will erode.

Large-scaled commercial fishing is not present on Cuba's north coast. For the little commercial fishing with nets that is present, it is prohibited to fish in the area where the Algae Halimeda grows by the ORPV.

Therefore, commercial fishing does not play a role in the erosion of the peninsula.

4.5.5 Ground water extraction

When water is extracted from the bottom, for example for consumption or cooling, the water level in the bottom will fall. As a result of this, the ground will settle and the land will relatively sink. This creates greater wave action close to the shore, causing erosion.

On the Peninsula de Hicacos, there is no ground water extraction. The necessary water is received from the mainland. Therefore, ground water extraction does not play a role in the erosion of the peninsula.

4.5.6 Extraction of raw materials

When raw materials are extracted from the bottom, the layers above the material will tend to subside resulting in a net sea level rise. Wave action will increase, erosion takes place and the dunes will move landwards.

Underneath the Peninsula de Hicacos and its surrounding, the bottom contains lots of oil. Commercial oil extraction is exploited. Several extraction facilities are situated within a range of 1 kilometer of the Paso Malo, see Figure 4-10, and other facilities
offshore are constructed. On the Peninsula itself, there is no extraction of oil because the area is determined by the government as a tourist area.

![Figure 4-10 Oil extraction near the Peninsula (Sept. 2003)](image)

Because no data are available on the amounts of oil that is extracted and no measurements have been made concerning to subsidence by oil extraction, this possible cause will not be taken into account in this research.

Therefore, the assumption is made that the extraction of raw materials plays no role in the erosion of the peninsula.

### 4.5.7 Sand mining

Often, sand is extracted from the coastal zone for the construction of constructions inland. If this sand is extracted far offshore, there is little influence on the beach and the beach profile will not change. If on the other hand the sand is extracted close to the shoreline, in the dynamic zone, it will influence the beach profile negatively. Wave action will increase and erosion will occur.

Nowadays, sand extraction in the dynamic zone of the beaches on the Peninsula de Hicacos is forbidden. In the 60’s and 70’s however, about 1 million m$^3$ sand was extracted from the dynamic zone.

Therefore, erosion by sand winning can not be ignored as it plays a significant role in the erosion of the peninsula.
4.5.8 Pollution

As said in the introduction, human being has always used the sea as a sink for the waste products of human society. In first, the quantity of pollution was low, but mainly after the Industrial Revolution the amount of pollution raised quickly, disturbing the natural balance in the sea. When pollution reaches a certain level, vegetation in the sea like for example the Algae Halimeda will die or decrease in size and number, and a sediment input of the system will be taken away.

Also, if there are dumping areas for in example building rubbish, artificial obstacles are created and sand transport will be disturbed.

On the Peninsula de Hicacos, pollution is present, mainly caused by the commercial activities on the island. Also, pollution is generated by the oil extraction plants in the neighborhood of the Peninsula and the huge oil refinery in Matanzas, see Figure 4-11.

![Figure 4-11 Pollution in Matanzas (Sept. 2003)](image)

Monitoring by the ORPV showed however that pollution in the past years was on an acceptable level, and did even decrease. In the past years, new norms have been made by the ORPV and an education program was started to make people aware of the negative effects of pollution, achieving good results. Also commercial shipping routes over the fields of Algae Halimeda were rerouted. Construction plans on the island nowadays always need the approval of the CISAM.
There can be concluded that pollution is present on the peninsula, but thanks to the efforts of the ORPV it shows a decreasing trend. Pollution does not play a significant role in the erosion.

4.5.9 Wrong executed nourishment

When sand is supplied to an eroding stretch of coast, the newly applied sand will tend to form a crust or blanket over the existing coastal formations. The newly applied sand will follow the physical laws that dominate the morphology in the same way as the existing sand. For this reason, major changes in the slopes and other coastal future are to be expected when the grain size of the supplied sand differs from the original material. Usually, this is not acceptable.

If sand is extracted from a wrong site, for example too close to the coast, it is also possible that nourishment will not achieve its objectives.

From June to August 1998, a twelve kilometer section of the beaches of the Peninsula de Hicacos was nourished. The sand that was used had a mean grain size of 0.38mm, while the original mean grain size was 0.26. The sand was extracted south of Cayo Mono, about five kilometers out of the coast.

The beach was monitored for five years after the nourishment by the Institute of Oceanology, and they concluded that after five years about 80% of the nourished sand was still on the beach profile. Therefore, it can be concluded that the nourishment was a success and there’s no sign of wrong executed nourishing on the peninsula. Therefore, it does not play a role in the erosion.

4.5.10 Insufficient Coastal management

Insufficient coastal management and a lack of legislation can cause severe damage to the beach because there is no control on the use (or abuse) of the coastal zone. The damage will not be directly caused by the bad management, but bad management could lead to for example disturbance of the dune-beach system or untested construction of groins.

On the Peninsula de Hicacos, until 1996 there was little co-ordination of the activities in the coastal zone. Nowadays, on the contrary, the ORPV and CISAM coordinate carefully all activities and are actively managing the coastal zone. Therefore,
nowadays bad coastal management is not present on the Peninsula and does not play a role in the erosion of the peninsula.

The results of bad coastal management of the past are taken in account in the Paragraph about disturbance of the dune-beach system (Paragraph 4.5.1).

### 4.6 Short term erosion

Short term erosion is most often caused by a sudden change in normal meteorological circumstances, for example during storms. These situations can cause severe damage to constructions on and next to the beach. Usually, the cross-shore transport as the movement of sediment is temporally.

The process of the dune-beach system in storm circumstances is described in 4.5.1. When looking at the short term erosion in this Paragraph, the assumption is made that no cross-shore gradient occurs, and so sediment is only transported in cross-shore direction.

Cross-shore gradients that may influence the longshore transport are considered in Paragraph 4.2.1.

In this paragraph, three possible causes of short term erosion are considered.

#### 4.6.1 (Extreme) Rainfall

When rainwater falls on the ground, it will either disappear into the ground or accumulate on it, finding its way into lower terrain. When extensive amounts of water fall down, for example during a storm, little water streams are formed, eroding their beds. Eventually the water streams will increase in size and stream out into the sea, dropping sediment into it.

After a while, most sediment will be transported again to the main land by for example wind, but until that point erosion is visible.

On the Peninsula de Hicacos, heavy rainfall is not a rare phenomenon. It rains 85 to 100 days a year, while most rain (80% of the annually 1320mm) falls during the wet season. Most heavy rainfall occurs during Hurricanes; for example, during Hurricane Michelle (2001) an amount of 234mm in 24 hours was measured.
In a big part of the peninsula, hard structures are built and water is quickly washed away onto the beach, eroding it as seen in subParagraph 4.5.2. In other parts of the peninsula, the upper layers consist of sand, and most water quickly disappears into the ground.

No signs of significant natural water streams in the direction of the beach are found at the peninsula. This can be easily explained by the slope of the peninsula: only in the first part of the peninsula the slope is such way that rain water flows in the direction of the beach.

Therefore, (extreme) rain fall does not play a significant role in the erosion of the peninsula as long as it is not falls down on hard structures. Rain falling down on hard structures is handled in subParagraph 4.5.2.

### 4.6.2 Hurricanes, cold fronts and other storms

The effect of storms is twofold: the sea level is elevated by low pressure, and due to increased wind velocity, wave action will increase too.

**Low pressure**

The normal air pressure pressuring on the sea surface is about 1013hPa at sea level. As a result of that, the water in the sea is compacted. When low pressures zones pass, pressure on the sea surface locally decreases while elsewhere normal pressure is remained. Due to the effect of communicating vessels, this results in an elevation of the sea level of approximately 1cm per hPa. Wave action near the shore will increase and erosion takes place.

Tropical lows, cold fronts and hurricanes but also other fronts drop the air pressure in the neighborhood of the Peninsula de Hicacos several times a year. Lowest pressures occur in the middle of hurricanes, values down to 888hPa have been measured (Hurricane Gilbert, 1988). For example, an elevation of 65cm due to low pressure occurred when Lily struck Cuba in 2002.

**Increased Wave action**

When wind velocities increase, the amplitude of the waves that are generated increases too. Higher waves come to shore, forcing more material to move offshore from the upper beach.
Wind velocities during hurricanes, cold fronts and other storms near the Peninsula de Hicacos vary but can produce significant wave heights up to 7.0m (measured when hurricane Michelle in 2001 passed).

Combined action of these new conditions will cause the beaches of the peninsula to respond dramatically through extensive offshore transport of material. This results in a substantial increase of cross-shore transport proportional to the difference between the existing beach profile and the equilibrium profile that matches with the new environmental condition. In the case of insufficient storage of material in the dunes or the presence hard structures in the dunes, damage can be severe.

After the storm has passed the beach will need sufficient time to get back to the original equilibrium situation. If new storms occur before the original beach profile was restored, the original profile will never be reached. In the past twenty-five years a clear increasing trend is visible if we plot the frequency storms occur against time. See Figure 4-12.

![Figure 4-12 Trend of increasing number of storms per year](image)

This means that the beach gets less time to recover after a storm, and maybe the old equilibrium situation is not reached nowadays. This result in a new equilibrium situation, with a new beach profile, sometimes giving the impression of erosion because of a sometimes steeper profile (after a storm the sand has a larger mean diameter) and the lesser amount of sand stored in the dunes. When not enough beach length is left after the storm, the sand will never be transported to the beach again by nature. See Paragraph 4.2.1. An increasing number of storms will cause an acceleration of the retreat of the coastline.
It can be concluded that hurricanes, cold fronts and other storms play a significant role in the erosion of the Peninsula de Hicacos, causing short term erosion. On some places on the peninsula, mainly in the neighborhood of old Varadero, this short term erosion may result in a structural redistribution of the sand in cross-shore direction.

### 4.7 Summary

In this chapter, all possible causes of the erosion of the Peninsula de Hicacos were split up into five groups, based on a division by Bird in 1993. After that, all possible causes were analyzed and it was determined whether the cause did or did not play a significant role in the erosion of the peninsula. The results are displayed in Table 4-1. When an assumption is made during the determination on the significance of a probable cause, crosses in the table are marked with (*).

<table>
<thead>
<tr>
<th>CAUSE</th>
<th>NO ROLE</th>
<th>NO SIGN. ROLE</th>
<th>A SIGN. ROLE</th>
<th>WHERE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradients in sediment transport</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-shore transport gradients</td>
<td>X(*)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longshore transport gradients</td>
<td></td>
<td>X(*)</td>
<td></td>
<td>Whole Peninsula</td>
</tr>
<tr>
<td>Wind</td>
<td></td>
<td>X</td>
<td></td>
<td>Whole Peninsula</td>
</tr>
<tr>
<td>Change in amount of river sediment</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Presence of irregularities in the profile</td>
<td>X(*)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Currents</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reef sediments</td>
<td></td>
<td>X</td>
<td></td>
<td>Whole Peninsula</td>
</tr>
<tr>
<td>Changes in bed material</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comminution</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qualitative change of river sediments</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Submergence</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>-----------------------------------------</td>
<td>-------</td>
<td>-------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global sea level rising</td>
<td>X</td>
<td>Whole Peninsula</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tectonic activity</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compaction</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human interference</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dune-beach disturbance</td>
<td>X</td>
<td>Mainly sector 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of a sufficient sewer system</td>
<td>X</td>
<td>Mainly sector 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Artificial interruption of the long shore current</td>
<td>X</td>
<td>Sector 1, near Paso Malo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial fishing</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground water extraction</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extraction of raw materials</td>
<td>X(*)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand winning</td>
<td>X</td>
<td>Whole Peninsula</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pollution</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrong executed nourishment</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bad Coastal Management</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short term erosion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Extreme) Rainfall</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hurricanes, cold fronts and other storms</td>
<td>X</td>
<td>Mainly sector 1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4-1 Summary determination of causes of erosion
5 Computation of the longshore transport capacity in UNIBEST

In chapter four the possible causes of the long-term erosion on the Peninsula de Hicacos were pointed out. In order to think of solutions for the erosion problem on the peninsula, one should know the amount and direction of the sediment that is transported. Therefore the main mechanism for the transportation of sediment: the longshore transport gradients are analyzed and quantified in this chapter.

In this chapter a model is made of the peninsula in a software model for longshore sediment transport called UNIBEST. This is necessary to make good predictions about the behavior of the coastline, and in a further stage to simulate solutions for the erosion problem in the future.

5.1 Introduction

The long shore transport is essentially caused by waves approaching at an angle to the coastline. Due to wave breaking there is a zone with an increased turbulence level where bottom material is brought into suspension. Once suspended the material is transported by a longshore current, caused by the breaking waves. The longshore current is therefore concentrated in the breaker zone.

In the past a lot of research has been done to attempt to determine the longshore transport rate. This rate depends on a lot of various parameters:

Wave characteristics

- $H_0$: Wave height at deep water
- $T$: Period of wave
- $Y$: Breaker index
In Paragraph 5.2 computations are made using the approaches of CERC, BIJKER and QUEENS. This is done in order to define which approach gives the best results to use for the model in UNIBEST. Moreover it serves to make a rough estimate of the amount of potential sediment transport and to gain insight in the used approach for the UNIBEST model. The difference between the methods is the way in which they take into account the abovementioned parameters. Furthermore the transport formulae are defined differently. For example the CERC formula gives the total longshore transport through the breaker zone while the BIJKER formula gives the sediment distribution in the breaker zone.

In Paragraph 5.3 the peninsula is modeled in a software model for longshore sediment transport, called UNIBEST. This model makes predictions about future erosion and accretion of the coastline on the Peninsula. This model will be validated with information obtained from field research and data from the Institute of Oceanology.

5.2 Estimate of the longshore transport capacity using different formulae

5.2.1 Introduction

The computations made in this Paragraph are made to make a rough estimate of the amount of potential sediment transport. The three most commonly used approaches for sandy beaches are taken into account to calculate the sediment transport capacity. It should be noted that a lot of assumptions had to be made in order to obtain results. Therefore these results are only rough estimations of the amount and direction of the sediment transport capacity and moreover to gain insight in the used formulas for the modeling in UNIBEST.

The three approaches used in this Paragraph are:

- CERC (1984)
- BIJKER (1971)
QUEENS (2000)

The wind generates waves, which are coming from the Atlantic Ocean and the Gulf of Mexico. In this calculation, four wind directions are taken into account: West, North West, North and North East.

The three approaches to calculate the longshore sediment capacity are based on different principles. The BJKER formula uses as main principle bottom friction to calculate a current velocity in longshore direction; with this a sediment distribution in the cross-section is obtained. The CERC and QUEENS formulas only look at the incoming wave height and direction, using a bulk-energy model.

The Institute of Oceanology of Cuba is responsible for all former investigations on the erosion of the peninsula. The institute showed an erosive trend of the entire beach along the peninsula for almost 30 years, it has estimated an erosion rate of the beach by comparison of beach profiles over the years. The conclusions that were drawn were an annual loss of 50,000m$^3$ sand per year.

5.2.2 Explanations and simplifications for the computations

5.2.2.1 Wave input for the calculation

According to literature, the calculation with these formulas can be done with two different ways to define the wave input\(^1\), one averaged weighted wave for each of the directions W, NW, N and NE, and for the whole wave climate from these directions:

- First only one weighted averaged wave per wind direction will be taken into account to facilitate the calculations (Table 5-1). To calculate this, data on direction, wave height and period, and percentages of occurrence are derived from GWS\(^2\). The weighted averaged significant wave height is calculated by multiplying the height of each wave by its percentage of occurrence. This is done for all wave heights and all added gives one mean wave height for this direction. The same is done to determine the wave periods. The results are shown in Table 5-1. In the calculation every wave causes sediment transportation, proportional to the occurrence of the representative direction.

---

\(^1\) Coastal Engineering Manual (2001)
\(^2\) Global Wave Statistics
After the addition of all singular transportations the total amount of sediment transportation is obtained.

<table>
<thead>
<tr>
<th>Angle of Approach, $\varphi_0$ (°)</th>
<th>Mean significant Wave height, $H_s$ (m)</th>
<th>Mean period, $T$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North east</td>
<td>-75</td>
<td>1.51</td>
</tr>
<tr>
<td>North</td>
<td>-30</td>
<td>1.71</td>
</tr>
<tr>
<td>North West</td>
<td>15</td>
<td>1.74</td>
</tr>
<tr>
<td>West</td>
<td>60</td>
<td>1.33</td>
</tr>
</tbody>
</table>

Table 5-1 Averaged waves derived from GWS

- Secondly the whole wave climate derived from GWS (Appendix 6) will be taken into account. Every possible wave height with its probability of occurrence is given (i.e. in the range 6-7 m with a period of 6.5 s), for every of these different wave heights a mean period is calculated by multiplying the period of each wave by its percentage of occurrence. Each of these specific waves produces a certain amount of sediment transport. In the end all the amounts of all these waves are added leading to the total amount of sediment. This takes a wave climate of 37 significant waves at deep water into account.

The difference between the results will be discussed later in this Paragraph in the conclusion.

5.2.2.2 Wave transformation

When waves approach the shore they respond to the bathymetry, changing shape, angle of approach and wave height. This process is called wave transformation. This behavior can be described with different formulas, qualified by ‘k·h’. (k·h is the wave number times the local depth.)

Outside the dynamic profile:
Inside the dynamic profile, until breaking:
Inside the breaking zone:

Deep water: $k \cdot h >> 1$.
Transitional zone: $k \cdot h \approx 1$.
Shallow water: $k \cdot h << 1$.

Estimation has to be done for the place that the waves break. A lot of investigation has been done after this subject all come to a relation between the wave height ($H_b$) and the local depth ($h_w$). For these computations the breaker index is estimated as:
\[ Y = \frac{H_{br}}{h_{br}} \approx 0.8^1 \]  

(Formula 5.1)

To determine this \( H_{br} \), a relation exists between the shoaling parameter \( K_s \), refraction parameter \( K_r \) and the wave height at deep water \( H_s \).

\[ H_{br} = K_s \cdot K_r \cdot H_s \]  

(Formula 5.2)

\[ K_s = \frac{c_{g0}}{c_g} \]  

(Formula 5.3)

\[ K_r = \frac{\cos(\phi_0)}{\cos(\phi_b)} \]  

(Formula 5.4)

Where:
- \( c_{g0} \) Group velocity of the waves in deep water (m/s)
- \( c_g \) Group velocity in transitional water (m/s)
- \( \phi_0 \) Wave angle of approaching waves in deep water (°)
- \( \phi_b \) Wave angle of waves in transitional zone (°)

To determine the depth at which breaking occurs an iteration process has to be done. First an estimate of this depth is made; with this the wavelength just at breaking \( (L) \) can be determined with formula 5.5.

\[ \frac{h}{L_0} = \frac{h}{L} \cdot \tanh\left(\frac{2\pi \cdot h}{L}\right) \]  

(Formula 5.5)

Where:
- \( h \) Water depth (m)
- \( L_0 \) Wavelength of the waves in deep water (m)
- \( L \) Wavelength of the waves in the transitional zone (m)

The wave angle at breaking \( (\phi_b) \) can be calculated as:

\[ \phi_b = \sin^{-1}(\tanh(k \cdot h_{br}) \cdot \sin(\phi_0)) \]  

(Formula 5.6)

Values for: \( \tanh(k \cdot h_{br}) \) and \( K_s \) also follow from formula 5.5.

---

1 "Short waves." Prof.dr.ir. J.A. Battjes; TU Delft, 2001
With the weighted averaged wave height and period, the values in Table 5-2 are obtained with wave angles, calculated to the perpendicular of the coast (30°).

<table>
<thead>
<tr>
<th>Direction</th>
<th>$H_0$ (m)</th>
<th>$T_0$ (s)</th>
<th>$\Phi_0$ (°)</th>
<th>$L_0$ (m)</th>
<th>$h_{br}$ (m)</th>
<th>$\Phi_b$ (°)</th>
<th>$K_r$ (-)</th>
<th>$K_s$ (-)</th>
<th>$H_b$ (m)</th>
<th>$\gamma$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>1.51</td>
<td>5.10</td>
<td>75</td>
<td>40.6</td>
<td>1.1</td>
<td>22.72</td>
<td>0.530</td>
<td>1.142</td>
<td>0.914</td>
<td>0.8</td>
</tr>
<tr>
<td>East</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>1.71</td>
<td>5.32</td>
<td>30</td>
<td>44.2</td>
<td>2.3</td>
<td>15.67</td>
<td>1.054</td>
<td>1.017</td>
<td>1.833</td>
<td>0.8</td>
</tr>
<tr>
<td>West</td>
<td>1.74</td>
<td>5.19</td>
<td>15</td>
<td>42.1</td>
<td>2.2</td>
<td>8.04</td>
<td>0.988</td>
<td>1.017</td>
<td>1.748</td>
<td>0.8</td>
</tr>
<tr>
<td>West</td>
<td>1.33</td>
<td>4.60</td>
<td>60</td>
<td>33.0</td>
<td>1.3</td>
<td>25.82</td>
<td>0.745</td>
<td>1.046</td>
<td>1.037</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 5-2 Calculation of $h_{br}$, $K_r$, $K_s$, and $\Phi_b$

5.2.2.3 Mean profile for the calculation

To simplify the computations, one mean profile for the whole peninsula is chosen.

This profile is taken in section 1 near the hotel Bella Costa (Figure 3-2, nr.12) this profile is shown in Figure 5-1. The profile is chosen from the six mean profiles from chapter (3.4) it contains a sandy beach and looks representative for the whole peninsula. Although other results are expected for other profiles, for a rough computation this profile is sufficient.

![Mean profile used for the peninsula of Hicacos](image)

Figure 5-1 Mean profile used for the computations
A straight line is added in this profile to simplify the computations. In this Paragraph (5.2) the assumption is made that this line will be representative for the beach profile on the whole peninsula (in the UNIBEST model different profiles along the peninsula are taken). The trend line has a slope of 1:60. So for every meter depth a distance of 60 meters from the shore is measured.

5.2.2.4 Velocity distribution in the surf zone

Water generally moves in a specific direction. The water movement is initiated by the driving forces. On the other hand there will be forces that try to resist this. The equilibrium of these forces in the longshore direction results in a constant current along the coast (the longshore current).

The driving forces can be:
- Radiation stress components (The contribution of horizontal momentum due to the waves)
- Wind forces
- Tide

The resisting forces can be:
- Turbulence (horizontal diffusion mechanism)
- Bottom friction (related to the velocity profile)

A prediction of the velocity distribution used in the original BÍJKER formula, from now on referred as BÍJKER (Original), is based upon an equilibrium between the driving force; Radiation stress and the resisting force; the bottom friction. This results in the following formula for the velocity distribution.

\[ V = 1.388 \cdot \frac{\sin(\phi_b)}{c_0} \cdot \frac{C}{\sqrt{f_w}} \cdot \gamma \cdot \sqrt{g \cdot h \cdot m} \quad \text{(Formula 5.7)} \]

in which:
- \( V \) Current velocity
- \( C \) Chezy coefficient
- \( Y \) Breaking index (-)
- \( h \) Waterdepth (m)
- \( m \) Beach slope (-)

\( f_w = \text{Jonsson's friction parameter} = \exp \left[ -5.977 + 5.213 \left( \frac{a_0}{r} \right)^{-0.194} \right] (-) \)
If we use this simplified assumption, then the longshore current velocity turns out to be a linear function of the water depth, within the breaker zone. Outside the breaker zone this current is zero.

Longuet-Higgins (1971) has predicted the velocity distribution obtained by including the turbulent forces in a dynamic equilibrium, the radiation shear stress gradient and bottom friction (leaving out wind and tide). Five steps have to be taken to calculate the velocity\(^1\).

1. \[ Y = \frac{y}{y_b} \]

   In which:
   \( y_b \) Distance from the shore where breaking occurs (-)
   \( y \) Distance from the shore (-)

2. \[ P = \frac{\pi \cdot \tan(\beta) \cdot N}{2 \cdot \alpha \cdot C} \]

   In which:
   \( \tan(\beta) \) Bottom slope (-)
   \( N \) Constant (=0.010)
   \( \alpha \) Empiric constant (=0.4)
   \( C \) Bottom friction factor (=0.010)

3. \[ p_1 = \left( -\frac{3}{4} \right) + \frac{9}{\sqrt{16} + P^{-1}} \]
   \[ p_2 = \left( -\frac{3}{4} \right) - \frac{9}{\sqrt{16} + P^{-1}} \]

   \[ A = \frac{1}{1 - 2.5 \cdot P} \]

---

\(^1\) Hugues, R. T., (2003): Estudio de diferentes métodos para la estimación de la capacidad de transporte de sedimentos en las playas. Aplicación a la playa de Varadero, Matanzas, Cuba.
\[ B_1 = \frac{p_2 - 1}{p_1 - p_2} \cdot A \]

\[ B_2 = \frac{p_1 - 1}{p_1 - p_2} \cdot A \]

From now the velocity can be distributed:

\[ V(Y) = A \cdot Y + B_1 \cdot Y^p \quad \text{For: } \quad 0 \leq Y \leq 1 \]  \hspace{1cm} \text{(Formula 5.8)}

\[ V(Y) = B_2 \cdot Y^p \quad \text{For: } \quad 1 \leq Y \leq \infty \]

If in reality the waves are not a regular (actually, they are irregular), the wave height will vary and the outer edge of the breaker zone will not be as well defined as is suggested in the former theories. This effect of this wave irregularity is much like that of the lateral turbulence; the velocity profile becomes wider and less sharply peaked.

The velocity distribution calculated with four representative waves (Table 5-1) and the mean profile (Figure 5-1), are shown in Appendix 7.

These two approaches of the distribution of the longshore velocity are used, first the simplified is used in BIJKER(Original) and second the Longuet-Higgins distribution in BIJKER(LH).

### 5.2.3 CERC formula (1984)

The amount of potential sediment transport in longshore direction in the breaker zone can be approximated by a formula developed by the Coastal Engineering Research Center (CERC) of the US Army Corps of Engineers.

The formula is based on the idea that longshore sediment transport is mainly driven by the incoming waves, rather than the tides and ocean currents. It indicates a correlation between the longshore transport rate \( S_x \), and the longshore component of energy flux at the outer edge of the surf zone.

The input parameters of the CERC-formula are only the incoming waves and the coastal profile. This might not be realistic, because the sediment transport must be expected to depend also on other parameters. The results from the CERC formula are strongly dependent of the empirical coefficients such as the 'A' coefficient and the breaking index \( \gamma \). With the CERC formula only the total transport rate can be computed and the distribution of sediment transport over width is not obtained.
The CERC formula is valid only for relatively long and strait beaches, where the alongshore differences in breaking wave height are small only. Moreover it must be applied to beaches with sand with mean grain size ranging from 0.2 – 1.0 mm. The grain size in Varadero ranges from 0.25-0.5 mm and the peninsula is relatively long, so an estimation of a long and strait beach is acceptable.

Moreover the formula does not take into account the currents that are not caused by breaking waves, such as tidal currents. There is only a small tidal current present in the peninsula. If the velocity of this current is neglected, this does not have a large impact on the system.

Taking this in consideration, the CERC formula can still be used for an estimation of the amount of potential sediment transport. Although there are more sophisticated expressions to calculate the longshore transport, the CERC formula is often applied mainly because of its easy use; it gives a quick estimate on the amount of sediment transport without many parameters required.

### 5.2.3.1 Formulas used for CERC

Many different versions of this formula exist; here the CERC formula presented in formula 5.9 will be used.

\[
S_c = A \cdot H_{10}^2 \cdot c_0 \cdot K_r^2 \cdot \sin(\phi_b) \cdot \cos(\phi_b) \\
\text{(Formula 5.9)}
\]

In which:
- \( A \) = Coefficient (-)
- \( S_c \) = Sand transport (m³/s)
- \( c_0 \) = Wave celerity in deep water (m/s)
- \( \phi_b \) = Angle between depth contours and wave crest at breaker line
- \( H_{10} \) = Significant wave height at deep water (m)
- \( K_r \) = Refraction coefficient
- \( \phi_0 \) = Wave angle with the coastline in deep water

### 5.2.3.2 Assumptions and Parameters

The range of the constant coefficient ‘A’ depending on the type of beach is advised to be: \( A = 0.014-0.035 \) m³/s.
Common factors used for A (Table 5-3):

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Characterizing wave height in deep water</th>
<th>A-Coefficient (with n=0.5 in deep water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original CERC (1973)</td>
<td>$H_{sig}$</td>
<td>0,014</td>
</tr>
<tr>
<td>Factor most used in the Netherlands</td>
<td>$H_{sig}$</td>
<td>0,020</td>
</tr>
</tbody>
</table>

Table 5-3 Different factors of A

The original value of 0.014 is based on prototype and model results in the past. Later on results pointed out that higher values of the ‘A’ coefficient are more realistic. The shore protection in 1984 recommends a value of 0.025, while the factor most used in the Netherlands is 0.02. A value of parameter ‘A’ of 0.015 is used for the computation.

The following amounts of sediment transport are obtained using the data from Table 5-3 for each wave direction.

5.2.3.3 Results computation with CERC-formula

Using the CERC formula, the following amounts of sediment transport is calculated with data from Table 5-1 for the four waves, one for each wave direction. The outcomes are given in Table 5-4.

<table>
<thead>
<tr>
<th>Wave direction</th>
<th>Percentage of Occurrence</th>
<th>Total sediment transport rate, $S_r$ (m$^3$/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North east</td>
<td>18,19 %</td>
<td>156.000</td>
</tr>
<tr>
<td>North</td>
<td>9,82 %</td>
<td>326.000</td>
</tr>
<tr>
<td>North West</td>
<td>4,93 %</td>
<td>-77.000</td>
</tr>
<tr>
<td>West</td>
<td>3,29 %</td>
<td>-43.000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>362.000</td>
</tr>
</tbody>
</table>

Table 5-4 Results with CERC, using four representative waves
From the calculations with the total wave climate the outcomes are listed in Table 5-5.

<table>
<thead>
<tr>
<th>Wave direction</th>
<th>Percentage of Occurrence</th>
<th>Total sediment transport rate, $S_c$ (m$^3$/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North east</td>
<td>18.19 %</td>
<td>295.000</td>
</tr>
<tr>
<td>North</td>
<td>9.82 %</td>
<td>501.000</td>
</tr>
<tr>
<td>North West</td>
<td>4.93 %</td>
<td>-151.000</td>
</tr>
<tr>
<td>West</td>
<td>3.29 %</td>
<td>-93.000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>552.000</td>
</tr>
</tbody>
</table>

Table 5-5 Results with CERC, using the whole wave climate

The calculations are presented in Appendix 8.

After these computations conclusions can be drawn about the direction and volume of the potential longshore sediment transport and the formation of the spit. This will be done in Paragraph 5.2.6 after the computations with the other formulae.

5.2.4 BIJKER Formula (1971)

The amount of potential sediment transport in longshore direction in the breaker zone can also be approximated by a formula developed by BIJKER.

BIJKER wanted to develop a formula to calculate the sediment transport as a function of a given wave field and a given longshore current irrespective of its origin (wave induced current or tidal current). The formula is able to predict the distribution of sediment transport over the profile as well as the total transport.

The bed load transport component was adapted from an existing transport formula for bed load under river circumstances. He divided this formula into a stirring parameter and a transport parameter and introduced the influence of the waves via a modification of the bottom shear stress, $\tau_c$, in the stirring parameter into $\tau_{cw}$.

BIJKER assumed that the combination of waves and currents causes a current velocity distribution which was logarithmic over the entire depth, this is used to calculate amounts for BIJKER (Original). The other calculation is done using a Longuet-Higgins distribution in the calculation of BIJKER (LH), see Paragraph 5.2.2.4.
The BIJKER formula is sensitive for the input of parameters such as the bottom roughness, material grain size, beach slope, and velocity distribution of the longshore current.

The bottom roughness influences the total transport in two ways: as the bottom roughness increases, the longshore velocity decreases; secondly, for a given current velocity, the BIJKER formula gives a lower sediment transport as the roughness increases. These two influences reinforce each other to yield the decreasing total sediment transport with increasing roughness.

An increase of the average bed material grain size decreases the total sediment transport, because the increase also influences the fall velocity 'w_s' for the suspended load and even the ripple factor 'μ' indirectly. Furthermore the diameter appears in the numerator of the exponent in formula 5.11.

Increasing the beach slope tends to increase the longshore current. This increased velocity will yield a higher sediment transport per unit width. The increasing beach slope narrows the breaker (and transport) zone, however so that the total sediment transport on a steep, narrow beach is little different from that on a flatter, wider beach. This conclusion justifies the use of a mean profile for the peninsula.

5.2.4.1 Formulas used for BIJKER

The BIJKER formula is built up of two components, namely, a bed load transport component and a suspended load transport component.

\[ S = S_b + S_s \]  
(Formula 5.10)

In which:

- \( S_b \) Bottom sediment transport (m³/m·s)
- \( S_s \) Suspended sediment transport (m³/m·s)

The formulation of the bottom transport '\( S_b \)' reads:

\[ S_b = \frac{b \cdot D_{50} \cdot V \cdot \sqrt{g}}{C} \cdot \exp \left[ -\frac{0.27 \cdot \Delta \cdot D_{50} \cdot \rho \cdot g}{\mu \cdot \tau_{sw}} \right] \]  
(Formula 5.11)
In which:

- $S_b = \text{Bed load transport} \quad (m^3/ms)$
- $b = \text{coefficient} \quad (-)$
- $D_{90} = \text{median (50%) grain diameter} \quad (m)$
- $V = \text{Local current velocity} \quad (m/s)$
- $r = \text{Bottom roughness (≈ 0.5-1.0 ripple height)} \quad (m)$
- $g = \text{gravitational acceleration} \quad (m/s^2)$
- $\Delta = \text{Relative density} \left[ (\rho_s - \rho_w) / \rho_w \right] \quad (-)$
- $\rho_s = \text{Mass density sediment} \quad (kg/m^3)$
- $\rho_w = \text{Mass density water} \quad (kg/m^3)$
- $\mu = \text{Ripple factor} \left( C/C_{90} \right)^{1.5} \quad (-)$
- $C_{90} = \text{Chezy coeff. based on} \quad D_{90} = 18 \log \left( \frac{12 \cdot h}{D_{90}} \right) \quad (\sqrt{m/s})$
- $D_{90} = 90\% \text{ grain diameter} \quad (m)$
- $\tau_{cw} = \text{Bed shear stress due to waves and current (time averaged)} \quad (m)$

The time averaged bed and shear stress due to the waves and currents $\tau_{cw}$ reads:

$$\tau_{cw} = \frac{\rho_s \cdot g \cdot V^2}{C^2} \left[ 1 + \frac{1}{2} \left( \frac{\xi \cdot u_s}{V} \right)^2 \right]$$

(Formula 5.12)

In which:

- $\xi = \text{Bijker's parameter} = C \cdot \sqrt{\frac{f_w}{2 \cdot g}}$
- $f_w = \text{Jonsson's friction parameter} = \exp \left[ -5.977 + 5.213 \left( \frac{a_0}{r} \right)^{-0.194} \right] \quad (-)$
- $C = \text{Chezy coefficient} = 18 \cdot \log (12 \cdot h / r_e) \quad (\sqrt{m/s})$
- $C_{90} = 18 \cdot \log (12 \cdot h / D_{90}) \quad (\sqrt{m/s})$
- $\mu = \text{Ripple factor} \left( C/C_{90} \right)^{1.5} \quad (-)$
- $h = \text{Local depth (m)}$
- $a_0 = \text{maximum horizontal displacement 'at the bottom'} = \frac{H}{2 \cdot \sinh (k \cdot h)} \quad (m)$
- $u_s = a_0 \left( \frac{2 \cdot \pi}{T} \right) = \text{orbital velocity near the bottom (m/s)}$
With the formulas above the amount of bottom transport in the section can be calculated.

To determine the ratio of bottom and suspended transport the Table in Appendix 9 is used. For this table it is necessary to calculate $z^*$ and the ratio $r/h$.

$$z^* = \frac{w}{\kappa \cdot V^*}$$  \hspace{1cm} \text{(Formula 5.13)}

In which:

- $V^*$ is the shear stress velocity which is adapted to the influence of the waves:
  $$V^* = V_{ssw} = \sqrt{\frac{t_{sw}}{\rho}}$$  \hspace{1cm} \text{(Formula 5.14)}

- $\kappa = \text{Constant of von Karman (-)}$
- $w = \text{Fall speed of grain (m/s)}$

BIJKER coupled the adapted bed load transport formula to the suspended load transport formula of Einstein. The suspended sediment can be shown to be directly proportional to the bed load transport. This results in:

$$S_s = 1.83 \cdot Q \cdot S_b$$  \hspace{1cm} \text{(Formula 5.15)}

The sediment transport in the whole cross section now reads:

$$S = S_b (1 + 1.83 \cdot Q \cdot S_s)$$  \hspace{1cm} \text{(Formula 5.16)}

### 5.2.4.2 Assumptions and parameter values

Since the BIJKER formula is a very extensive calculation, only the calculation with the four representative waves will be done (Table 5-1) and not a calculation with the whole wave climate.

The value of coefficient $b$ in formula 5.11 has been discussed a lot of times. Values ranging between 1 to 5 have been suggested. A commonly suggested value is 1 for outside the breaker zone, and 5 for inside the breaker zone. These values will be used in the calculation.
The parameters used in the calculation are shown in Table 5-6.

The velocity distribution will be calculated with a simplified theory as well as a Longuet-Higgins velocity distribution, as described in Paragraph 5.2.2.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>0.80000</td>
<td>(-)</td>
</tr>
<tr>
<td>$\rho_{\text{sand}}$</td>
<td>2700</td>
<td>(kg/m$^3$)</td>
</tr>
<tr>
<td>$\rho_{\text{water}}$</td>
<td>1025</td>
<td>(kg/m$^3$)</td>
</tr>
<tr>
<td>$D_{50}$</td>
<td>0.00026</td>
<td>(m)</td>
</tr>
<tr>
<td>$D_{90}$</td>
<td>0.00040</td>
<td>(m)</td>
</tr>
<tr>
<td>$r$</td>
<td>0.05000</td>
<td>(m)</td>
</tr>
<tr>
<td>$w_s$</td>
<td>0.04550</td>
<td>(m/s)</td>
</tr>
</tbody>
</table>

Table 5-6 Parameters used for the calculation with BIJKER

5.2.4.3 Results computation with BIJKER-formula

Using the BIJKER formula, the following amounts of sediment transport is calculated with data from Table 5-1 for the four waves, one for each wave direction. The outcomes are given in Table 5-7.

<table>
<thead>
<tr>
<th>Wave direction</th>
<th>Percentage of Occurrence</th>
<th>S (m$^3$/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE</td>
<td>18.19 %</td>
<td>112.000</td>
</tr>
<tr>
<td>N</td>
<td>9.82 %</td>
<td>179.000</td>
</tr>
<tr>
<td>NW</td>
<td>4.93 %</td>
<td>-50.000</td>
</tr>
<tr>
<td>W</td>
<td>3.29 %</td>
<td>-37.000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>204.000</td>
</tr>
</tbody>
</table>

Table 5-7 Results using BIJKER, with original theory for the velocity distribution

The calculations with the Longuet-Higgins distribution are listed in Table 5-8.
Wave direction | Percentage of occurrence | $S$ (m$^3$/year)
---|---|---
NE | 18.19 % | 55.000
N | 9.82 % | 61.000
NW | 4.93 % | -28.000
W | 3.29 % | -7.000
Total | | 81.000

Table 5-8 Result using BIJKER, with Longuet-Higgins velocity distribution

The calculations are presented in Appendix 10.

### 5.2.5 QUEENS formula (2000)

Another formula to calculate the amount of sediment transport is the QUEENS formula. The formula is a variant of the CERC-formula, made by the Canadian Coastal Sediment Study. Kamphuis (1991) derived an expression that includes the effects of wave period (or wave steepness), beach slope and grain size. The formula was derived from small-scale hydraulic model tests and was found to be valid for available field results, but is highly sensitive for empirical parameters such as the QUEENS-coefficient and the breaking index. The QUEENS formula takes into account the incoming waves, sand characteristics and beach slope.

The QUEENS formula has a tendency to over predict transport for gravel beaches because it does not include a critical shear stress (it assumes that particles move even for small wave conditions, which is true for sand, but not for gravel), but the peninsula has got sandy beaches. Moreover the QUEENS formula is only valid if:

- no tidal currents are present
- Straight beach, no groin-fields or offshore breakwater present
- Plane beach, no complicated breaker-bar systems

In the area of interest (Peninsula de Hicacos) there is some tidal influence, but it is not really much (tide difference of 0.20m). Breakwaters are present at Paso Malo and the depth contours differ along the peninsula, but taking this in consideration, the QUEENS formula can still be used for an estimation of the amount of potential sediment transport.
5.2.5.1 Formulas used for QUEENS

A dimensional analysis of bulk sediment rate ‘Qs’ in the turbulent breaking zone leads to the following general formula:

\[
\frac{Q_s}{\rho \cdot H_{sh} \cdot T_{op}} = 1.3 \cdot 10^{-3} \cdot \left( \frac{H_{sh}}{L_{op}} \right)^{-1.25} \cdot m_s^{0.75} \cdot \left( \frac{H_{sh}}{D_{50}} \right)^{0.25} \cdot \sin^{0.35}(2 \cdot \alpha_s) \]

(Formula 5.17)

In which:

- \( Q_s \) = sediment transport rate (kg/s)
- \( \rho \) = density of water (kg/m\(^3\))
- \( H_{sh} \) = significant breaking wave height (m)
- \( T_{op} \) = peak period of the spectrum on deep water (s)
- \( L_{op} \) = wavelength in deep water related to the peak frequency of the wave spectrum (m)
- \( m_s \) = bottom slope (-)
- \( D_{50} \) = median grain or rock size (m)
- \( \alpha_s \) = angle of wave incidence in deep water (°)

The parameter of interest of this calculation is not the sediment transport rate (Qs in kg/s), but the amount of sediment transport in cubic meters (S in m\(^3\)/s). For this reason one has to divide Qs by the density of the sediment and the fraction of volume occupied by the material (1-porosity).

\[
S = \frac{Q_s}{(1-p) \cdot \rho_s}
\]

S = sediment transport (m\(^3\)/s)

\( p \) = porosity of the material (-)

\( \rho_s \) = density of the material (kg/m\(^3\))

This leads to the following expression:

\[
S = \frac{1.3 \cdot 10^{-3}}{(1-p) \cdot \rho_s} \cdot \frac{\rho \cdot H_{sh}^3}{T_{op} \cdot L_{op}} \cdot m_s^{0.75} \cdot \left( \frac{H_{sh}}{D_{50}} \right)^{0.25} \cdot \sin^{0.35}(2 \cdot \alpha_s)
\]

(Formula 5.18)
5.2.5.2 Assumptions and parameters

According to Kamphuis (1986) the value of the QUEENS-coefficient was determined on $1.3 \cdot 10^{-3}$ or 41000 for results per year. According to Kamphuis (1991) this value should be 64000.

A re-analysis of Schoonees (1996), who analyzed more data, resulted in a value of $1.6 \cdot 10^{-3}$ (or 50000) for mild wave conditions and/or coarse material. This should be the right value to calculate the potential sediment transport per year. For exposed sites, 65000 is a better value. In this calculation the QUEENS-coefficient is determined on $1.3 \cdot 10^{-3}$ m/s, because on the beach of Varadero the wave conditions are not mild and there is no coarse bottom material present.

To calculate the total amount of sediment transport, first other parameters have to be known. The other parameters are calculated with CRESS.

As explained in the introduction of this chapter, there are two calculations made with two different input parameters. The first calculation is made with only four representative waves, one wave for every relevant direction. In the second calculation the total wave climate is taken into account. This climate is obtained from the Global Wave Statistics.

For the calculations the following parameters were used as presented in Table 5-9.
QUEENS formula

\[ \rho_w = 1025 \text{ kg/m}^3 \]
\[ \rho_s = 2650 \text{ kg/m}^3 \]
\[ H_{sb} = \text{Global wave statistics (Area 32)} \]
\[ T_{\text{op}} = \text{Global wave statistics (Area 32)} \]
\[ m_b = 60 \]
\[ D_{50} = 260 \mu\text{m} \]
\[ \alpha_b = \text{depending on wind direction} \]

CREASE

\[ H_s = \text{significant wave height (m)} \]
\[ T_0 = \text{wave period (deep water) (s)} \]
\[ \theta_0 = \text{wave angle (deep water) (°)} \]
\[ \text{Occurrence} = \text{wave occurrence} \]
\[ C_o = \text{propagation speed (deep water) (m/s)} \]
\[ L_0 = \text{wave length (deep water) (m)} \]
\[ \theta_b = \text{wave angle (when breaking in °)} \]
\[ 2A_b = 2\times A_b \text{ (in rad)} \]
\[ h_b = \text{breaking depth (m)} \]
\[ HB = \text{wave height (when breaking) (m)} \]
\[ S(\frac{m^3}{s}) = \text{sediment transport (in m}^3/s) \]
\[ S(\frac{m^3}{yr}) = \text{sediment transport (in m}^3/yr) \]

Table 5-9 Used parameters for Cress and the QUEENS formula

5.2.5.3 Results computation with QUEENS-formula

Using the QUEENS formula, the following amounts of sediment transport is calculated with data from Table 5-1 for the four waves, one for each wave direction. The outcomes are tabulated in Table 5-10.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Percentage of Occurrence</th>
<th>S (m$^3$/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>18.19 %</td>
<td>-5.100</td>
</tr>
<tr>
<td>NW</td>
<td>9.82 %</td>
<td>-13.900</td>
</tr>
<tr>
<td>N</td>
<td>4.93 %</td>
<td>46.500</td>
</tr>
<tr>
<td>NE</td>
<td>3.29 %</td>
<td>24.000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>51.500</td>
</tr>
</tbody>
</table>

Table 5-10 Results using four representative waves

From the calculations with the total wave climate the outcomes are listed in Table 5-11.
Peninsula de Hicacos

Computation of the longshore transport capacity in UNIBEST

<table>
<thead>
<tr>
<th>Direction</th>
<th>Percentage of Occurrence</th>
<th>S (m³/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>18.19 %</td>
<td>-10.240</td>
</tr>
<tr>
<td>NW</td>
<td>9.82 %</td>
<td>-24.500</td>
</tr>
<tr>
<td>N</td>
<td>4.93 %</td>
<td>66.670</td>
</tr>
<tr>
<td>NE</td>
<td>3.29 %</td>
<td>49.380</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>81.300</td>
</tr>
</tbody>
</table>

Table 5-11 Results using the whole wave climate

The total calculations of both computations are presented in Appendix 11.

5.2.6 Conclusions

The results of the computations are represented in Table 5-12.

<table>
<thead>
<tr>
<th>Sediment transport capacity (m³/y)</th>
<th>CERC</th>
<th>BIJKER (original)</th>
<th>BIJKER (Lonquet-Higgins)</th>
<th>QUEENS</th>
<th>Oceanology Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Representative weighted waves</td>
<td>362.000</td>
<td>204.000</td>
<td>81.000</td>
<td>51.500</td>
<td>x</td>
</tr>
<tr>
<td>Whole wave climate</td>
<td>552.000</td>
<td>x</td>
<td>x</td>
<td>81.300</td>
<td>50.000</td>
</tr>
</tbody>
</table>

Table 5-12 Results computations

Direction

All computations show a potential longshore transport capacity in western direction. This direction of the transport is completely understandable with respect to the most occurring wind direction. So the spit of the peninsula is formed in a western direction, this seems not understandable at first sight, but is possible since the peninsula used to be a group of separated small limestone islands that were connected over time by sand transported from algae fields, eventually resulting in this peninsula.

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Amounts

When we look at the amounts there are a couple of things to be noticed.

- The difference between the results calculated with four representative waves and the results obtained using the whole wave climate. This difference is due to the non linear dependence of the transport equation on breaking wave height. This will lead to higher results. When using the whole wave climate the waves are more accurately represented, causing higher transport capacities and thus higher erosion rates. So when calculating sediment transports in UNIBEST the whole wave climate should be used.

- The different results between the formulas and the department of Oceanology. If we compare all results with an assumption that BIJKER gives slightly higher results when calculated using the whole wave climate. One can notice that BIJKER (LH), QUEENS and the data of the measurements made by the institute of Oceanology are within the same range, and the CERC and BIJKER (original) are far out of this range. This indicates that CERC needs calibration of the ‘A’ coefficient and that the assumption that BIJKER (Original) made neglecting turbulence forces to compute the current velocity is not good for a computation of the peninsula. BIJKER (LH) and QUEENS can be used to make calculations on the sediment transport for the peninsula in the UNIBEST model.

- The distribution of the sediment transport in the profile shows the essential difference in approach of the formulas. The BIJKER formula uses bottom shear stress to calculate a sediment distribution in the profile. While the CERC and QUEENS formula look at the incoming wave height and direction, using a bulk-energy model, showing no difference in amount of sediment transport through a unit width in a cross section. So with the CERC and QUEENS formula only the total transport can be computed and the distribution of sediment transport over the profile is not obtained.

Final conclusions

So the conclusion can be made that in the UNIBEST model, the approach of BIJKER is suggested, with an appropriate velocity distribution and the whole wave climate. This approach will probably give the best results for the sediment transport on the peninsula.
5.2.7 Summary

Calculations to estimate the amount of potential sediment transport have been done with the CERC, BIJKER, and QUEENS formulae using:

- Four averaged waves from the directions W, NW, N and NE.
- Using the whole wave climate from W, NW, N and NE.

The results show a potential long shore transport capacity in western direction and are presented in the table below.

<table>
<thead>
<tr>
<th>Sediment transport capacity (m³/y)</th>
<th>CERC</th>
<th>BIJKER (original)</th>
<th>BIJKER (Longuet-Higgins)</th>
<th>QUEENS</th>
<th>Oceanology Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Representative weighted waves</td>
<td>362.000</td>
<td>204.000</td>
<td>81.300</td>
<td>51.500</td>
<td>x</td>
</tr>
<tr>
<td>Whole wave climate</td>
<td>552.000</td>
<td>x</td>
<td>x</td>
<td>81.300</td>
<td>50.000</td>
</tr>
</tbody>
</table>

The results are compared with each other and with the result from the Institute of Oceanology of Cuba. From the comparison the conclusion is drawn that the BIJKER formula, using a velocity distribution current in the long shore direction, which takes into account turbulent forces, is able to give good results in the UNIBEST program.
5.3 UNIBEST

In this chapter only the assumptions made for the model and the results derived from it are discussed. The way UNIBEST works and what input is required are given in Appendix 12. In the former Paragraph a decision is made that the BIJKER approach gives good results, therefore the model will only use this approach.

5.3.1 Comparison of a simplified model in UNIBEST with the results from the former computations

A comparison of the results with the same simplified model in UNIBEST LT is made with the results from the estimate in Paragraph 5.2. To see if the UNIBEST model gives the same results as the computations with BIJKER (LH). For results of the simplified UNIBEST model see Appendix 13.

As in Paragraph 5.2 in the first case only one representative wave from each of the four directions is taken into account, in the second run all the wave data. The same profile is used as in the former Paragraph. The dynamic border is placed at a depth of 11 meter (672 m out of the coast).

With the BIJKER approach the amount and direction of the sediment transport is calculated. The same parameters were used. The results of the LT run in UNIBEST are presented in Table 5-13. The UNIBEST model gives a negative result in western direction while the estimate gave a positive result for this direction. Therefore the sign of this estimate is changed in Table 5-13.

<table>
<thead>
<tr>
<th>Wave direction</th>
<th>Computation BIJKER (LH) (m³/y)</th>
<th>BIJKER (UNIBEST) (m³/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE</td>
<td>-55.000</td>
<td>-37.600</td>
</tr>
<tr>
<td>N</td>
<td>-61.000</td>
<td>-68.500</td>
</tr>
<tr>
<td>NW</td>
<td>28.000</td>
<td>+22.200</td>
</tr>
<tr>
<td>W</td>
<td>7.000</td>
<td>+10.100</td>
</tr>
<tr>
<td>Total</td>
<td>-81.000</td>
<td>-84.000</td>
</tr>
<tr>
<td>Whole wave climate</td>
<td>(-)</td>
<td>-121.400</td>
</tr>
</tbody>
</table>

Table 5-13 Comparison UNIBEST with the estimate from Paragraph 5.2
If we compare the velocity distribution found in UNIBEST with the one from the computations one can see a difference for the computation of the velocity distribution in:

- $V(\text{hand})$, used in BIJKER(Original),
- $V(\text{L-H})$, used in BIJKER(Longuet-Higgins)
- $V(\text{UNIBEST})$ used in BIJKER(UNIBEST).

![Velocity distribution (NE)](image.png)

**Figure 5-2 Sediment distribution (NE)**

The UNIBEST model uses a basic momentum equation (formula 5.19) to describe the longshore current distribution in the approach of BIJKER.

$$\frac{d}{dx} S_{xy} + \rho g \frac{dh_y}{dy} + \rho \frac{g}{C^2} |V_{nx}| = 0$$  \hspace{1cm} \text{(Formula 5.19)}

In which the second part ($dh_y/dy$) is due to the tide. But as can be seen from figure 5-2, the surfaces under the graphs from Longuet-Higgins and UNIBEST are approximately the same. One can conclude from this that the same amounts of potential sediment transport are taken into account. Therefore it is valid to use the UNIBEST velocity distribution to make further computations.
5.3.2 Applicability of UNIBEST

To calculate the sediment transport (long shore) along the coast of Peninsula de Hicacos the software modules UNIBEST LT (Long shore Transport) and UNIBEST CL (Coastline development) are used. UNIBEST LT will calculate the amount of sediment transport due to wave and current conditions, and the data from these calculations are used in UNIBEST CL to predict how the coastline will develop for a certain period and how that affects the local transport.

UNIBEST is applicable for large (hundreds of kilometer), medium (tens of kilometers) and small scale (few kilometers) beach areas. The Peninsula is typically a medium scale model. In a medium model the impact of coastal defense measures over a time of a few decades can be modelled. No short-term effects can be modeled (like the difference between summer and winter profiles and storm-induced erosion in which cross-shore sediment transport sediment due to storms is the main cause) but only the long-term evident trend of the coastline. The same goes for tidal current-dominated coasts and the local scour around hard structures.

The model can be calibrated by comparison with other models and calculations (estimations) and the tuning of parameters like the bottom roughness.

5.3.3 The Peninsula de Hicacos model

In a model the wave (all waves) and current conditions, the beach profiles and the coastal structure (like rock formations and houses built on the dunes) will be taken into account.

5.3.3.1 Assumptions made in UNIBEST LT

For the input of UNIBEST TC assumptions have to be made before the model can be applied. Below, each part of the assumptions of the input is discussed.

Wave heights
The wave heights will be borrowed from the GWS as well as the division in wave height: from 0.5 m to 8.5 m in steps of 1 m (0.5 is the mean of 0-1 meter which is used in the GWS)

---

1 Source: UNIBEST manual, 1994
Wave periods
The wave period plays only a minor role\(^1\) in the littoral drift equation in comparison with the wave direction and height. Therefore the weighted mean wave period (determined for each of the four directions) can be used. The wave periods given in GWS are not in \(T_s\), but in \(T_m\) that will be used as input for the wave period in UNIBEST.

Duration of waves
The data in the GWS give the chance of occurrence of a certain wave from a direction (in thousandth from one direction, with each direction in percentages). In UNIBEST the duration of a wave must be given in number of days (range: 0.01-365). The data from the GWS are therefore converted to chance of occurrence in days.

Wave angle
The angle between the normal on the wave front and the normal on the coast is defined as the wave angle. For a coast that runs east-west the wave angle will therefore differ from a coast which runs south-north. In Paragraph 3.7 (waves) is concluded that the directions from which the most important waves arrive are from four directions: East, Northeast, North and Northwest.

![Figure 5-3 Gulf of Mexico with Cuba and Peninsula de Hicacos](image)

When looking at the Peninsula’s size and location in the strait of Florida, it can be concluded that the Peninsula is small in comparison with the distances over sea from these four directions. Also it is clear that there are no obstacles like small islands in

\(^1\) Short Course on Principles and Applications of Beach Nourishment (1988)
front of the Peninsula which can influence the waves from these four directions. Therefore it is concluded that on the entire northern coast of the Peninsula the same waves arrive from deep water. The only factor that differs along the coast is the orientation of the coast where the waves arrive. For each coast section and wave directions the wave angle has been determined considering the wave direction and the coastal angle.

Tides
The mean tidal amplitude is used, namely 0.20m. The same goes for the tidal velocity which is 0.10m/s.

Elevation
The large elevations due to atmospheric lows never coincide with the high waves caused by these winds. This is caused by the fact that in the centre of a low the pressure is lowest but wind velocities in the centre are not highest (and therefore waves neither). Therefore the influence of the elevation is considered to be zero for all waves.

Dynamic border
Because of the fact that the depth is determinative of the border between the static and dynamic zone (see Paragraph 3.4 on bathymetry, the dynamic border depth is 11.2m), for each profile the distance from the coast to the dynamic border is determined.

Truncation transport border
The truncation transport border is the border from where the sediment will be moved. The UNIBEST manual gives that generally this boundary is the same as the dynamic border as will be assumed here.

Profiles
The six profiles were earlier described (Paragraph 3.4) and derived from different sources of information (see chapter on bathymetry). Each profile is different and will therefore have a different value of the transport value in each of the six rays.

Wave parameters
The default file from UNIBEST is used and the bottom roughness ($k_b$) is taken in 0.1m which appeared from observations made in situ and are given normal values in the UNIBEST manual (the influence of the bottom roughness will be checked later and used for calibration). For the bottom friction 0.01 is a common value.

Breaker index
The breaker index is found with the formula:

$$\gamma_{br} = 0.5 + 0.4 \times \tanh (33 S_0) \quad \text{(Formula 5.19)}$$

With:

- $S_0$: Deep water steepness.

With for example $H_s = 3.5$ meter, the $H_{rms} = 0.707 \times H_s = 2.47$m and the obtained wavelength is 75m.

The following values are found:

- $S_0 = 0.0329$

The breaker index found is: $\gamma_{br} = 0.81$. This value will therefore be taken as the breaker index.

Transport parameters

In Table 5-14 the parameters are given for the formula of BIJKER.

<table>
<thead>
<tr>
<th>Formula of BIJKER</th>
<th>Value of parameter</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{50}$</td>
<td>310</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>$D_{60}$</td>
<td>600</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>Bottom Roughness $k_c$</td>
<td>0.05</td>
<td>$m$</td>
</tr>
<tr>
<td>Sediment fall velocity</td>
<td>0.045</td>
<td>$m/s$</td>
</tr>
<tr>
<td>Criterion $H_s/h$ (deep water)</td>
<td>0.07</td>
<td>-</td>
</tr>
<tr>
<td>Coefficient $b$ (deep water)</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Criterion $H_s/h$ (shallow water)</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td>Coefficient $b$ (shallow water)</td>
<td>5.00</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5-14 Coefficients used in the BIJKER formula

A remark is made that the used bottom roughness is $k_c = 0.5 \cdot k_0$; $0.5 \cdot 0.1 = 0.05 m$.

5.3.3.2 Assumptions made in UNIBEST CL

Assumptions also have to be made for the input in UNIBEST CL to come to a model that can predict the coastal development over a certain period.

For UNIBEST CL assumptions have to be made about the following data:

Coastal sections
For the case of the Peninsula de Hicacos, the coast is divided into six different sections, based on different coastal angles (the waves reach the coast under a different angle), beach characteristics and different cross-shore profiles. Below is the description on how the area is schematized (which sections are distinguished, with what dimensions and what kind of structures and natural irregularities are present). The coastal area considered in the model is the entire stretch from the beach near Hotel Oasis (in the west) to Punta Frances.

There are six sections defined where different profiles are used these are areas where the bathymetry and wave conditions are comparable, and therefore different transport values are found for every ray.

Section 1:
The coast runs in western direction from hotel Oasis to Kawama beach for 4 km. The distance from Hotel Oasis to the Paso Malo is about 500 m and the distance from the Paso Malo to Kawama beach is 3,5 km. The angle of this coast is 0 ° with the equator.

The whole part of the peninsula (the rest of the beach in the model) from Kawama to Punta Francés has an angle of -30 ° with the equator into northeastern direction.

Section 2:
The beach from Kawama to Calle 23 is 1 km long.

Section 3:
This is the coast between Calle 23 and 37 (the number of the streets) where hotels have been built on the dunes several decennia ago. This length of this section is about 1.2 km.

Section 4:
From Calle 37 to Palacio de la Rumba the beach consists of sand. The area is approximately 8 km long.

Section 5:
From Palacio de la Rumba to Punta Chapelin the coast consists of rocky points running into the sea and in between small (some hundred of meters) sandy beaches. This area is approximately 3,5 km long and is modeled as an coast with every 700 meters a breakwater with the length of 20 m and blocking percentage 80% because of their irregular structure.
Section 6:
The area from Punta Chapelin to Punta Francés consists of sandy beaches and is about 3.5 km long.

The model of the coastline and the six sections thus described is as shown in Figure 5-4.

The six transport rays are placed in the middle of each section.

![Figure 5-4 different sections](image)

Coastal characteristics
In the model as described above some assumptions had to be made about how to model the coast itself and the hard structures along the coast:

On the western side of the Paso Malo, in front of hotel Oasis are located two small groins, both in bad condition (Figure 5-5). The western is 10 m long and will not be considered in the model. The eastern is about 40 m long and will be put in the model.
At both sides of the mouth of the Paso Malo are breakwaters. The western runs about 40 meters into the sea and the eastern 75 meters, both in a direction of south-southeast to north-northwest. The reason for this difference is the complex flow-pattern around the breakwaters and sand mining for annual maintenance. These breakwaters are modeled perpendicular to the coast.

On the dunes between Calle 23 and 37 (the number of the streets) hotels have been built on the dunes several decennia ago. The walls of these hotels obstruct the sand transport during high waters and especially storm surges. Because of the little influence they have on the long shore transport in comparison to the cross shore transport capability, they will be placed in the model but will probably have little influence (only when the local erosion is so high the coast erodes as far as the hotel walls. The length of this area is about 1 km.

From Palacio de la Rumba to Punta Chapelín the coast consists of rocky points running into the sea and in between small (at most a few hundred of meters) sandy beaches. This area is approximately 3,5 kilometer long and is modeled as an coast with every 700 meters an breakwater with length 20 m and blocking percentage 80% because of their irregular structure. These assumptions will be evaluated later and their length or characteristics will be changed if necessary.

Boundary conditions
For both sides of the model area boundary conditions have to be applied. For both sides the same condition is applied which is that the beach at the boundary doesn’t change in width over time ($\delta y/\delta t = 0$ and thus: $\delta Q_s/\delta x = 0$). This is done because west of Hotel Oasis (the western boundary) the coast exists of low rocky terraces
and no erosion is possible. The eastern boundary (Punta Frances) exists also of a rocky cliff and cannot erode therefore.

![Graph showing longshore transport capacity](image)

**Figure 5-6: Model of the Peninsula**

### 5.3.4 Calculation of transport capacity at the six sections

The six sections have different values for the sediment capacity due to the different profiles and coastal angles. The following values were found:

<table>
<thead>
<tr>
<th>Potential Transport Capacity</th>
<th>Qₜ BIJKER (m³/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>section 1</td>
<td>-89.300</td>
</tr>
<tr>
<td>section 2</td>
<td>-135.900</td>
</tr>
<tr>
<td>section 3</td>
<td>-114.100</td>
</tr>
<tr>
<td>section 4</td>
<td>-111.200</td>
</tr>
<tr>
<td>section 5</td>
<td>-111.300</td>
</tr>
<tr>
<td>section 6</td>
<td>-102.500</td>
</tr>
</tbody>
</table>

**Table 5-15 Characteristics of the six sediment transport capacities**

**Sensitivity of the bottom roughness (kₖ):**

The bottom roughness is assumed to be 0.1 m as the UNIBEST manual proposed. The Qₜ calculated with that is -89.300 m³/yr (The negative sign shows a transport from East to West). If the bottom roughness is increased from 0.10 m to 0.12 m the
value of Qs is -83.900 m³/yr. With kₙ is 0.08 the Qₛ is -96.600 m³/yr. This means that there is some sensitivity of the value for kₙ. In the UNIBEST manual it is said that the bottom roughness is one of the parameters that can be used to calibrate the model. If the results of the model are not of the right magnitude in comparison with other data this value has to be adapted. For now, the value is assumed to be 0.1 as advised by the UNIBEST manual.

**Distribution and characteristics of Qₛ:**

In the Figures below for each of the six sections more detailed information can be found.

For every section the equilibrium angle of the coastline is given. It depends on the wave characteristics as well as on the bathymetry. Also the distribution of the sediment transport along the profile can be seen.

The green arrow gives the border for 50% of the transport and also the value for the dynamic border is given.

The dotted line gives the cumulative course of the sediment capacity, which can be used to determine the amount of sediment that will be stopped by for example a breakwater. Of course the value for the total sediment transport capacity is given (k(m³/(m·yr))) for every section as well (Table 5-15).
Figure 5-7 transport capacity at section 1

- transport: -135.9 [k(m²/m³)]
- Dynamic boundary X = -825.0
- c1 = 0.005
- c2 = 0.016

Figure 5-8 transport capacity at section 2

- transport: -114.1 [k(m²/m³)]
- Dynamic boundary X = -990.0
- c1 = 0.004
- c2 = 0.016

Figure 5-9: transport capacity at section 3
Figure 5-10: transport capacity at section 4

Figure 5-11: transport capacity at section 5
5.3.5 Distribution of variables along the profile

The UNIBEST LT model can give information about the distribution of certain parameters along the profile (for each ray and each wave), these parameters are:

- $H_s$ (Significant wave height m)
- Wave angle at approaching the shore (°)
- $V$ (longshore water velocity m/s)
- $U_{rms}$ (Orbital velocity m/s)
- $Q_s$ (Sediment transport m$^3$/ms)

An example of the results obtained are given for area three and an (example) wave from the northwest with $H_s = 2.50$m and $T = 5.20$s (see the figures 5-13 to 5-18).
Figure 5-13 Profile at area 3

Figure 5-14 \( H_s \) (Significant wave height)

Figure 5-15 Wave angle at approaching the shore
Figure 5-16 $V$ (longshore water velocity)

Figure 5-17 $U_{ms}$ (Orbital velocity near bed)

Figure 5-18 $Q_s$ (Sediment transport)

Peninsula de Hicacos
Computation of the longshore transport capacity in UNIBEST
The graphs can also be given as numerical data and for every wave and all six sections but these are not given here because of the huge number of data.

For every section the wave transformation of one wave is presented in Appendix 14.

5.3.6 Transport capacity at the whole Peninsula

The so called transport rays are applied to the six places on the map (Paragraph 5.3.3.2) and interpolated in-between by the program. It then gives the following result for the Peninsula:

![Image of sedent transport capacity along the Peninsula](Figure 5-19: The sediment transport capacity along the Peninsula)

The arrows give an indication of the wave climate: the larger the arrow, the higher the mean wave compared to the local sediment transport capacity. The direction of the mean wave is indicated by the angle of the arrows. The distance of the arrow to the coast indicates the distance to the dynamic boundary.

From Figure 5-19 it can be concluded that because of the larger distance to the dynamic border in front of the ‘revetment’ (Historic Varadero) in comparison with the neighboring areas (it can also be seen in the values for $Q_e$ for the six sections in Table 5-15) there will be some erosion of the coast. This is due to the larger distance of the dynamic boundary to the coast (it gets deeper more quickly in the neighbouring areas). This will be checked further in the report.
The values for the sediment capacity can also be plotted along the coast in a graph (see Figure 5-20 and Table 5-16):

![Graph showing the amount of Qs against distance from the western boundary.]

**Figure 5-20: Amount of Qs per year**

<table>
<thead>
<tr>
<th>Distance X (m)</th>
<th>Location at the Peninsula</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>Breakwater (40 m) just east of Hotel Oasis</td>
</tr>
<tr>
<td>1200</td>
<td>Breakwaters (85 m) at the mouth of the Paso Malo</td>
</tr>
<tr>
<td>4129</td>
<td>Hotel Kawama</td>
</tr>
<tr>
<td>5170</td>
<td>Calle 23</td>
</tr>
<tr>
<td>6475</td>
<td>Calle 37</td>
</tr>
<tr>
<td>12206</td>
<td>Palacio de la Rumba</td>
</tr>
<tr>
<td>15559</td>
<td>Punta Chapelin</td>
</tr>
<tr>
<td>18379</td>
<td>Punta Frances</td>
</tr>
</tbody>
</table>

**Table 5-16 Distances along the coast with their location**

It is clear that all values in the graph of the Peninsula are negative which means that (at the northern coasts) the net sediment transport is in western direction. The direction of the transport may be changing over the year but that is not considered here. A large gradient of the line between two points means a large difference between those two points in input and output of sediment. It is a matter of erosion if the gradient is positive and accretion if the gradient is negative.

From figure 5-20 is can be concluded that large positive gradients in the graph (therefore places of erosion) occur near the breakwaters of the Paso Malo, between Calle 23-37 en locally near every Rocky point between Palacio de la Rumba and
Punta Chapelin. How much the erosion is at these spots will be looked at in the next Paragraph.

5.3.7 Trend of the coastline in the future

To see what will be the consequences if no measures are taken, UNIBEST was run for a period of 50 years. The reason it was simulated for 50 years is that it is the same period as the lifespan of the hard measures so the simulation makes clear what the actual effects are during this period. Also nourishment combined with a maintenance program can be simulated for the same period.

In earlier runs a short period was looked at with many calculations (and therefore output) points. If the run is over a longer period certain irregularities can cause the coast to show sudden large fluctuations. This can be prevented by using less calculation points. The results however don't change numerically although at less points output is given also. This was done for the 50 year run and in order to get a stable run between Calle 20 and Calle 37 there are now 3 output points (instead of 5 in some earlier runs).

5.3.7.1 Regression of coastline

The regression of the coastline was plotted along the coast of the Peninsula from the western boundary (300m west of Hotel Oasis) to the eastern boundary (Punta Frances)(see figure 5-21).
5.3.7.2 Critical areas

Is can be seen from the graph that the largest problems due to erosion can be expected near Hotel Oasis (west of the Paso Malo), a part of Historic Varadero and near every rocky point.

The biggest problems at Historic Varadero are in the graph on the long term. A remark is made here that in reality an amount of sand is removed from the east side of the breakwaters near the Paso Malo and placed on the beaches more to the east. If this was not done (as in the model) the coastal angle east of these breakwaters would approach the local equilibrium angle and more sand would pass the mouth of the Paso Malo.

5.3.7.3 Rocky points

Because of the assumptions made about their location, size and blocking percentages, the data cannot be used numerically and only qualitative. To rule out the possibility that their influence is of significance in the more western parts of the Peninsula, another run was done for a period of 50 years without the presence of the rocky points and the results made clear that they had no influence on the transport downstream (from a point about 200 meter west of Palacio de la Rumba).
This means that due to the small length and reduced blocking percentage their influence is very local.

### 5.3.8 Comparison data of Institute of Oceanology

To get a final idea whether the UNIBEST model of the Peninsula reflects the real situation of sediment transport, its results have to be compared with other data. If not, the model has to be calibrated with for instance the bottom roughness. These other data consist of visual observations (qualitative evaluation), measurements and calculations of the Institute of Oceanology. The results from the Institute are given in three criteria:

- The locations of the most severe erosion rates
- The trend of coastal regression per year
- The amount of sediment lost from the system due to erosion per year

In the next table (5-17) a comparison is made between the data from the institute of Oceanology and the UNIBEST model.
Table 5.17 Comparison between data from Institute of Oceanology and the UNIBEST model

<table>
<thead>
<tr>
<th>Criterion:</th>
<th>Institute of Oceanology</th>
<th>UNIBEST model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Hotel Oasis (west of Paso Malo)</td>
<td>1 West of Paso Malo (400m)</td>
<td></td>
</tr>
<tr>
<td>2 Kawama - Calle 7 (200m)</td>
<td>2 Calle 20-37 (1200m)</td>
<td></td>
</tr>
<tr>
<td>3 Calle 23 – 37 (1000m)</td>
<td>3 Rocky points (east of each)</td>
<td></td>
</tr>
<tr>
<td>4 Hotel Melia Varadero (Rocky point)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Hotel Sol Palmeras (Rocky point)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.20 m/ year (Historic Varadero)</td>
<td>1.45 m/ year (Historic Varadero)</td>
</tr>
<tr>
<td>3</td>
<td>50.000 m³/year</td>
<td>89.000-135.000 m³/year</td>
</tr>
</tbody>
</table>

Criterion:
- The locations of the most critical spots observed by the Institute of Oceanology (IO) are at the same as the critical spots from the UNIBEST model. The only differences with the results of the Institute of Oceanology appear east of Hotel Kawama (near Calle 7) where erosion is observed by IO and UNIBEST predicts accretion. This is explained by the fact that the coast doesn’t have such a sudden change of coastal angle as modeled in UNIBEST. It is actually seen in UNIBEST that the change in coastal angles becomes more gradual over time (as the coast is in reality). If the coastal angle change would be modeled more gradually, the transition between erosion to accretion would be over larger distance so that near Hotel Kawama possibly erosion would occur in small amounts (still smaller then near Calle 23-37). If one looks at the problems at Hotel Kawama this should be taken into account.

- The trend of coastal regression in Historic Varadero observed by the Institute of Oceanology is 1.20m per year. The results of UNIBEST indicate that the maximum regression in Historic Varadero is in the area of Calle 20-37 and is 1.45m per year. Noted is that these are the highest values and they are somewhat higher than observed by the IC, but a slightly higher value is always better then an underestimated value in the case of coastal defense. Still the difference is acceptable because this is the maximum regression and in the same area the average regression is about 1.10m per year. So the average is more close to the value of the observed regression.
• The calculations by the IO of the amount of sediment lost by the structural erosion estimated 50,000 m³/year. The values computed in UNIBEST were between 89,000 and 135,000 m³ per year depending on the section along the coast. These values are higher than the IO determined. The value of 50,000 m³/year calculated by the IO is based upon measurements of the coastal profile for several decades and visual observations of (among other things) the regression of the coastline. These measurements were done to a maximum of 80 m into the sea. This means that not the entire dynamic zone is looked at. The dynamic zone is in reality between 500 and 1000 meters out of the coast. Therefore actually a larger sediment capacity is found in every section than could be observed with these measurements. Therefore the result from UNIBEST on the loss of sediment from the system is accepted to be of the right magnitude.

5.3.9 Final conclusion

The final conclusion is that UNIBEST model gives an accurate impression of the locations where erosion can be expected (qualitative comparison) and also of the regression of the coastline (quantitative comparison). For quantitative data on the area near Calle 7 (Hotel Kawama) the bend in the coast has to be more gradual. Furthermore it is concluded that the model is based on the right principles according to the evaluation made between the simple model and the calculations made by "hand". The hand calculations also give a good insight in the processes that takes part in the transport of sediment in longshore direction. The loss of sediment from the system estimated by the model is slightly higher than the observations by the Institute of Oceanology (IO) showed. This is explained by the measurements done by the IO which do not cover the entire dynamic zone. The values for the local erosion near the rocky points are arguable because of the rough assumptions made on the location and characteristics of these rocky points. Because there are no reliable data at these points to calculated the regression of the coastline, no quantitative comparison could be made. It is therefore concluded that the model is applicable for the area from Hotel Oasis to Punta Chapelin (Hotel Kawama excluded) and can be used to give preciser data modeled of the Peninsula.
5.4 Summary

Computations were done to calculate the sediment transport capacity. Different formulas were used: CERC, BIJKER and QUEENS and their results were compared.

<table>
<thead>
<tr>
<th></th>
<th>CERC (m³/yr)</th>
<th>BIJKER (original) (m³/yr)</th>
<th>BIJKER (Longuet-Higgins) (m³/yr)</th>
<th>QUEENS (m³/yr)</th>
<th>Institute of Oceanology (m³/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four representative</td>
<td>724.000</td>
<td>204.000</td>
<td>81.000</td>
<td>51.500</td>
<td>x</td>
</tr>
<tr>
<td>weighted waves</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whole wave climate</td>
<td>1104.000</td>
<td>x</td>
<td>x</td>
<td>81.300</td>
<td>50.000</td>
</tr>
<tr>
<td>(GWS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-18 Summary of the calculations of the amount of potential transported sediment

From these results it is concluded to use the Bijker formula in the UNIBEST model.

In UNIBEST (using the BIJKER formula) first a simplified model was used (straight slope of the bottom profile) with the same input parameters as in the computations, which gave the following result:

<table>
<thead>
<tr>
<th>Wave direction</th>
<th>Computation BIJKER (LH) (m³/yr)</th>
<th>UNIBEST BIJKER (m³/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE</td>
<td>-55.000</td>
<td>-37.600</td>
</tr>
<tr>
<td>N</td>
<td>-61.000</td>
<td>-68.500</td>
</tr>
<tr>
<td>NW</td>
<td>28.000</td>
<td>+22.200</td>
</tr>
<tr>
<td>W</td>
<td>7.000</td>
<td>+10.100</td>
</tr>
<tr>
<td>Total</td>
<td>-81.000</td>
<td>-84.000</td>
</tr>
</tbody>
</table>

From this data is concluded that the model can be used to simulate the longshore sediment transport at the Peninsula of Hicacos.

UNIBEST model

A model of the Peninsula of Hicacos was made (with all wave conditions) For the six different sections defined the following transport capacities were found:
UNIBEST sections | \( Q_i \) (in m\(^3\)/yr)
--- | ---
Transport capacity section 1 | -89.300
Transport capacity section 2 | -135.900
Transport capacity section 3 | -114.100
Transport capacity section 4 | -111.200
Transport capacity section 5 | -111.300
Transport capacity section 6 | -102.500

After a run of 50 years without any measures three critical zones appeared (see graph below):

West of the mouth of the Paso Malo around Hotel Oasis
In a part of 1200 m in Historic Varadero (Calle 20 to Calle 37)
Near every rocky point between Palacio de la Rumba and Punta Chapelin

The coastline of the Peninsula after 50 years

The erosion after 50 years appeared largest in Historic Varadero (about 70 m).

The output of the UNIBEST model is comparable with data observed by the Institute of Oceanology on three criteria:

1. Places of critical zones (places subject to large erosion)
2. Amount of regression of the coastline (Institute of Oceanology: 1.20 m per year)
3. Loss of sediment out of the system due to longshore transport (Institute of Oceanology: 50.000 m\(^3\) per year)

Project group CF015
The data found on these three criteria with the UNIBEST model are:

1. Critical zones near Hotel Oasis, Historic Varadero (Calle 20 to Calle 37) and locally near every rocky point
2. 140m per year in Historic Varadero (highest value at the Peninsula de Hicacos)
3. Around 100,000 m³ per year
6 Quantification of the other causes of erosion

In chapter five the longshore gradients that cause erosion at the peninsula were handled. In this chapter, the other possible causes of erosion that were identified in chapter four are quantified.

6.1 Introduction

The other possible causes for the long-term erosion of the peninsula that were pointed out in chapter four are:

- Reef sediments
- Wind
- Global sea level rising
- Dune-beach disturbance
- Sand mining

Each paragraph in this chapter will deal with the quantification of one possible cause.

6.2 Reef sediments

The Algae Halimeda fields play an important role in the supply of sediment to the peninsula, because approximately 40% of the sand on the beach originates from these Algae. The amount of sediment that is produced by these Algae was estimated on 10 kg/m²/year by the Oceanographic Institute. With a density of 2700 kg/m³, this implies a production of sediment of 3700 m³/km²/year.

The Algae grows in big fields on the sea bottom, located Northeast of the peninsula at a depth of approximately 10m. No exact data is known about the size of the fields,
though an estimation given by the ORPV indicates a total area of 6 km². This would mean a total production of 22,200 m³ of sediment a year.

The sediment will travel to the beach from the different fields, and the time it takes to reach the beach will differ. However, because it is a process that has been going on for a very long time, it is assumed that every year the same amount of sediment reaches the beach.

6.2.1 Evaluation

The estimations of both the Oceanographic institute as well as the ORPV are very rough. Real values of the production therefore may differ a lot from the estimations, as not much research has been performed.

6.2.2 Conclusion

A certain amount of sediment is received each year from the Algae Halimeda, but the exact amount is very uncertain. Further on in this research, when looking for solutions for the erosion problems, the production of sediment will be neglected and therefore considered to be zero. The positive contribution of the production will not be considered during the designing process.

6.3 Sediment transportation by wind

When wind blows over the beach, sediment is taken with it. When this sediment is blown over the dunes or there is no dune present on the beach, sand is blown inland. In this Paragraph, a calculation is made to determine the amount of sand that on the Peninsula de Hicacos in this way is lost from the beach.

6.3.1 Computation

The total amount of sand transported by wind is calculated with the use of CRESS\(^1\). In CRESS the White equation\(^2\) is used, and the influence of cohesion between grains

---

\(^{1}\) White equation (1993), in 1993 corrected by Blumberg and Greeley

\(^{2}\) White equation (1993), in 1993 corrected by Blumberg and Greeley
is ignored. Cohesion leads to an increasing critical shear velocity and thus leads to a decreasing rate of sand transport.

Only winds from west to north-northeast will be considered in this research, because those are the directions of wind that produce sand transport inland. See Figure 6-1

Figure 6-1 Wind directions that are considered in the transport of sand inland

There are two data sets on wind available, viz. the data from Varadero airport and the data set derived from the Global Wave Statistics. In this case only the wind directions from west to northeast are taken in consideration; therefore the data from Varadero airport is used (Paragraph 3.6.3.3, evaluation).

For all wind directions, the component perpendicular to the coast have to be determined in order to calculate the amount of sand that is blown in this direction. See Figure 6-2, where the example is given for winds from the west. Clearly is visible that to calculate the component perpendicular to the coast of the peninsula, the wind velocity has to be multiplied by the sinus of alpha.
Peninsula de Hicacos

Figure 6-2 Gradient perpendicular to the coast form winds of the west

The following reduction factor can be calculated from these angles of approach:

<table>
<thead>
<tr>
<th>Direction</th>
<th>Reduction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>West</td>
<td>0.50</td>
</tr>
<tr>
<td>West North West</td>
<td>0.79</td>
</tr>
<tr>
<td>North West</td>
<td>0.97</td>
</tr>
<tr>
<td>North North West</td>
<td>0.99</td>
</tr>
<tr>
<td>North</td>
<td>0.87</td>
</tr>
<tr>
<td>North North East</td>
<td>0.61</td>
</tr>
<tr>
<td>North East</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table 6-1 Reduction factors wind

Applying these reduction factors leads to wind velocities perpendicular to the coast that are significantly lower than the basic velocities, resulting in a lower transport of sand.

With the distribution of wind velocities and directions, it is now possible to calculate the amount of sand that is blown inland. The constants and variables in Table 6-2 form the input of CRESS:
1. Density of air 1.25 kg/m³  
2. Density of the sand 2700 kg/m³  
3. Height above surface (where wind is measured) 10 m  
4. Wind velocity at height z Varies  
5. Roughness length for the surface 0.20 m  
6. Empirical constant (k is an empirical constant with value 0.018 for narrow upright standing vegetation or 0.046 for small round trunkless plants) 0.035  
7. Projected hor. covering of vegetation 15%  
8. Empirical coefficient (The value of A is estimated at 0.1-0.118 for grains larger than 0.1 mm. For grains smaller than 0.1 mm A increases.) 0.11  
9. Grain diameter 0.31 mm  
10. Surface slope 5°  
11. Angle of internal friction of sand 33°

Table 6-2 Wind parameters used in Cress

The values of 1, 2, 3, 4, 8, 9 and 11 are known. Values for 5, 6, 7 and 10 are estimated by the use of photos. The mean value of the estimated range is used in the calculation, as a range of values is determined from the photos. See Table 6-3.

<table>
<thead>
<tr>
<th>Variable/ Constant</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness length for the surface</td>
<td>0.10 – 0.30 (m)</td>
</tr>
<tr>
<td>Empirical constant k</td>
<td>0.30 – 0.40 (-)</td>
</tr>
<tr>
<td>Projected hor. coverage of vegetation</td>
<td>10 – 20 (%)</td>
</tr>
<tr>
<td>Surface slope</td>
<td>5 – 6 (-)</td>
</tr>
</tbody>
</table>

Table 6-3 Ranges of estimated variables

Reduced wind velocities are obtained from Varadero airport, and for each direction the amount of sediment that is transported each year is calculated with CRESS. The results are shown in Table 6-4.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Reduction factor</th>
<th>Sediment transport inland in m³/m/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>West</td>
<td>0.50</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Project group CF015 160
West North West | 0.79 | 0.8
North West     | 0.97 | 2.6
North North West| 0.99 | 2.0
North          | 0.87 | 8.6
North North East| 0.61 | 0.7
North East     | 0.26 | 14.8

Table 6-4 Sediment transport inland

Each year, a total amount of 14.8m³ of sand is blown inland by winds at every meter of coast of the peninsula. With a approximately 12 km of beaches, this results in a total amount of about 175.000m³ of sand that is blown inland by wind on the peninsula de Hicacos.

Most of this sand will be trapped in the dunes, or new dunes are formed where sediment is trapped by vegetation. However, on places where the dunes are destroyed or not fully developed, a part of the sand will be blown into the peninsula.

It is impossible to determine the amount of sand that is trapped by the dunes or vegetation on the peninsula. Also, some of the sand blown inland will be blown back to the beach by winds from the west, resulting in a lesser loss of sand. Active care of the dunes and its vegetation should prevent the sand from blowing inland.

It is clear that disturbance of the dune-beach system can cause a significant loss of sand, as approximately 175.000m³ of sand is blown over the beach each year.

6.3.2 Evaluation wind transport

By the computation of the amount of sand that is transported by wind, some of the input variables are estimated making use of photo’s, and can therefore be considered as not very accurate. A sensitivity analysis is made. The sensitivity of the output for these variables is plotted in Figure 6-3.
Figure 6-3 Sensitivity analysis of the output for $z_0$, $k$, $C$ and $\phi$

Figure 6-3 shows that the output is highly sensitive to the estimated variables. Variances within the ranges of $z_0$ and $k$ can double or halve the amount of sediment transport; variances within the range of $C$ and $\phi$ have even bigger impact.

The simplification to split every wind direction up in a direction longshore and a direction perpendicular to the coast also influences the results of the computation. Winds with enough velocity to transport sand in their direction but with gradients perpendicular to the coast with insufficient velocity to transport sand are neglected. Therefore, a lesser amount of sand transport is found as a result of this simplification.

Variable differences along the coast of the Peninsula, though occurring, are not taken in account. Also, it is striking that the fetch of the wind over the beach is not included in the formula.
No winds in longshore direction are taken in account, though they will transport sand along the coast, maybe influencing for example the sand diameters.

6.3.3 Conclusion on wind transport

From the computation follows a total amount of approximately 175.000m³ of sand that is blown in the direction of the dunes each year. Dominating in this process are winds from the North and Northwest. Most of the sand is trapped by dunes and their vegetation, but losses can occur; these losses can theoretically be as much as 14.8m³ of sand per meter of beach. Active care of the dunes and its vegetation can prevent this loss.

The calculation is not very accurate, because it is very sensitive to the estimated variables and constants and a simplification is made. However, it gives a good impression of the amount of sand that is blown away by wind and indicates that disturbance of the dune-beach system can bring about a significant loss of sand.
6.4 Global sea level rise

Erosion of the beach (decrease in volume of beach material) will cause recession of the coast line (movement landward). One classic example of beach recession results from sea level rise. Higher water levels allow larger waves to come closer into shore, resulting in erosion of the top portion of the profile to adjust to the more severe wave conditions. It is possible to estimate the net beach recession accompanying the sea level rise by assuming that the wave climate remains the same and the beach profile retains its shape. This beach profile eventually must rise with the water level and the volumes of sand required to raise the profile in the foreshore must come from landward movement of the profile.

6.4.1 Regression of the coastline

BRUUN’s Rule\(^1\) gives an estimate of the regression of the beach due to sea level rise (Figure 6-4):

\[
R = \frac{x_c h}{(d_d + d_c)}
\]

(Formula 6.1)

With

\[
d_c = 1.6 H_{s,12}
\]

(Formula 6.2)

R: Regression of the beach (m)

x_c: Distance out to the closure depth (width of the active profile) (m)

h: Sea water level rise (m/year)

d_d: Dune height (m)

d_c: Closure depth, seaward limit of the active beach profile (m)

H_{s,12}: Significant wave height which occurs 12 hrs/yr on average (m)

\(^1\) “Coast Erosion and the development of beach profiles”, P. BRUUN, 1954
Figure 6-4 Beach profile recession from water level rise according to BRUUN

Values used for the calculation of the Regression are:

\( x_c \): 650 m, determined from \( d_c \) and the mean profile used for the Peninsula de Hicacos.

\( d_d \): 3m, determined from photographs and plots made by the Institute of Oceanology

\( d_c \): 11.2 m

\( h \): 2.9 \( \times \) 10\(^{-3} \) m/year

This results in a regression of the coastline of 0.132 m/year.

6.4.2 Volume of transported sand

To determine the sand volume that is transported due to Sea Water level rise, two simplifications are made. (Figure 6-5)

Figure 6-5 Simplification of the beach recession due to sea level rise

These simplifications are:

1. The whole beach profile moves over the distance \( R \) land inwards
2. The area between the profiles is the area that is eroded.
With these simplifications, the total eroded volume due to sea level rise can be calculated.

This results in an erosion of 0.937 m³/m/year. So, for the total peninsula with 12 kilometer of beach, an approximate volume of 11.500 m³/year is lost by sea level rise.

### 6.4.3 Evaluation of global sea level rise

BRUUN’s rule is very approximate because:

The distance out to the closure depth, $x_c$ (or the width of the active profile) is computed according to formula 6.2: Which makes $x_c$ very sensitive to $d_c$. The final slope AB will be very flat and hence the triangle ABC will contain quite a volume of sand that is ignored in this calculation. There is no offshore sediment movement as a result of currents, tides and gravity. An eroded volume of sand is expected to produce the same volume when deposited.

Also, to determine the volume of eroded sand of the beach simplifications have been made to the beach profile of BRUUN. These simplifications cause an overestimation of the amount of eroded sand by sea level rise.

BRUUN\(^1\) gives an indication for the size of coastal regression due to sea level rise, see Table 6-5.

<table>
<thead>
<tr>
<th>Rise per year (mm)</th>
<th>Shoreline recession per year (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1000-1500</td>
</tr>
<tr>
<td>20</td>
<td>2000-3000</td>
</tr>
<tr>
<td>30</td>
<td>3000-4500</td>
</tr>
<tr>
<td>100</td>
<td>10000-15000</td>
</tr>
</tbody>
</table>

Table 6-5 Shoreline recession as a function of sea level rise

It is clear that a regression of 0.132m/year due to a sea level rise of 2.9mm/year is within the boundaries of BRUUN.

\(^1\) BRUUN, P (1986). Worldwide impact on sea level rise on shore stability
There can be concluded that the simplification of BRUUN's profile provides an indication of the size of the amount of eroded sand by sea level rise.

6.4.4 Conclusions

From the computation follows a total amount of approximately 11,500 m³/year of sand eroded by sea level rise on the Peninsula de Hicacos, and a coast regression of 0.132 m/year. This is an overestimation that is very subjective to the value of the closure depth of the active profile (dₜ), but provides an impression of the size of the amount of eroded sand by sea level rise.

6.5 Sand winning

In the 60's and 70's about one million m³ of sand was extracted from the beaches of the Peninsula de Hicacos for construction works. Nowadays however, sand extraction from the beach or elsewhere in the dynamic zone is prohibited; therefore, no sand extraction takes place, so the amount of sand extracted each year is zero.

The long-term effects of the extraction of the sand 35 years and longer ago are difficult to measure. Maybe the beach profiles nowadays would be different when the sand was not extracted, or the shape of the coast would be different. None of these effects are taken in account in this research; up to date profiles and other data is used, and because of the long time that has passed a new equilibrium should be reached, and long-term effects of the extraction should be within the used data.

6.5.1 Conclusion

The total amount of sand that is extracted by man nowadays is zero. Effects of the winning of one million m³ sand in the past are already in the data used in the other calculations and can therefore be neglected.

6.6 Summary

Reef sediments contribute a specific amount of sediment to the Peninsula de Hicacos. Estimations about the total amount of this sediment, indicating an input of about
22.200 m³/year are so rough that in this research the input of sediment by the Algae Halimeda is neglected.

Wind is able to transport a lot of sediment each year; about 175.000 m³ can be blown landinward. Most of that sand will be trapped by dunes and vegetation. It is clear that when the dunes or the vegetation is destroyed, a lot of sediment can be lost by wind transport.

Sea level rise results in a shoreline retreat of 13.2 cm/year. This leads to a approximately loss of sand of 11.500 m³/year. This sand is transported in cross shore direction.
7 Critical Zones

In this chapter the critical zones on the Peninsula de Hicacos are determined. These are the zones where erosion is most severe. The most critical zone is selected and the potential sediment transport in this zone is quantified. Further on in this research, solutions for this most critical zone will be handed.

7.1 Critical Zones

In this Paragraph, the critical zones are pointed out and described. At the end, a choice is made what critical zone will be looked at when looking for solutions.

7.1.1 Location and description of the critical zones

In Paragraph 3.1 the Peninsula de Hicacos is divided in three areas (see Figure 7-1). This division was based upon two former nourishment programs, one in the Western part and another in the Eastern part, executed in respectively 1998 and 2003. Between these three sections different characteristics of the beach can be distinguished.

![Map of Varadero](image)

Figure 7-1 Map of Varadero (source: Nautical chart British Admiralty)

Based upon the calculations with the programs UNIBEST and CRESS three critical zones can be distinguished. Those three zones show the most erosion in the models. Two of them are situated in section 1 in Figure 7-1, and the other one can be found
in the second section. In the third section, almost none erosion has been noted. Also because of the limited amount of activity at the moment in section three, most attention has been paid to the first two zones, and that is why UNIBEST models only the first two sections. The critical zones with most erosion in these two sections are:

**Zone 1**
The first zone is situated near the Paso Malo breakwater. Actually, it is located between the breakwaters of the Paso Malo and hotel Oase.

**Zone 2**
The second zone is located between Calle 20 till Calle 37 in Historic Varadero, the area where a lot of construction has been done in the dunes.

**Zone 3**
The third zone is between Palacio de la Rumba and Punta Chapelin, where the beach changes constantly from rocky to sandy. Between the rocky points continuing erosion is showed.

The exact locations of these zones are displayed in Figure 7-2.

![Figure 7-2 Location of the critical zones](image)

The Institute of Oceanology pointed out five critical zones: the difference between the results in this research and the critical zones pointed out by the institute is explained in Paragraph 5.3.8.
7.1.2 Characteristics of the critical zones

Before a choice can be made about which zone will be looked at more precisely, some characteristics of the zones are presented.

Zone 1
The first zone has one specific characteristic: the presence of the Paso Malo breakwaters. In the eastern part of the zone, in the updrift of the Paso Malo breakwaters, there is accretion, while on the other side erosion occurs. This is mainly due to fact that the most occurred wind direction is from the northeast, creating a sediment transport from east to west. There is only one hotel that suffers from the erosion in this section, videlicet Hotel Oasis. The safety of the hotel is not in danger, because its location is directly behind the dune on the landward side. The only negative influence of the structural erosion in this first zone therefore is the changing beach surface throughout the year.

Zone 2
The second zone is also located in the first section (see Figure 7-2). Characteristic for this zone is the presence of houses and hotels on the dunes and seawalls located very close to the waterline. These objects are situated in the dynamic zone, which causes a real threat for the inhabitants of the houses and tourists in the hotels, because the structures interfere with the natural dynamic system.

Another negative aspect of the objects situated close to the waterline is the small area of the beach left for recreational activities. Therefore the average amount of beach per tourist (10 m²), indicated by the ORPV¹ cannot be guaranteed in this zone. The presence of the rocky terraces above and just below the water surface will accelerate the process of erosion locally.
The economic value of the area is quite significant, because about 50 hotels and houses are present. Some buildings have been left already, but quite a significant number of houses and hotels are still occupied.

Also, the level of tourist activities on the beach should be taken into account when the economic value of the area is discussed. At the moment the beach is just a small strip between the seawalls and the waterline. The historic value of the area can not be forgotten; the houses and hotels were built during the 50's and 60's when the tourist development started.

¹ Officina para la Recuperación de la Playa de Varadero
Zone 3
The last critical zone is situated in section 2 (see Figure 7-2). Structural erosion occurs from Palacio de la Rumba to Punta Chapelín, because the coastline changes frequently from sandy beaches to rocky points, causing longshore gradients. Several large four- and five-star hotels are situated in this zone. So, the economic value of this zone is very large. A significant number of tourists visit this zone throughout the year, so the beach must be in good shape and the width of beach must be sufficient. The historic value of the spot can be neglected, because the hotels exist for only a couple of decades. On the other hand, the economic value of this zone is very high.

7.1.3 Most critical zone

In this subparagraph a choice has to be made which critical zone will be of interest in the next phases of the project. It is impossible to create a solution for every critical zone, due to a lack of time; that is why a choice has to be made.

In the following chapters the critical zone from Calle 20 to Calle 37 (Critical zone two) will be the subject, because it is the most critical one. The houses and hotels on the dunes are directly threatened by the retreating shoreline and the volume of beach area in this zone is the smallest one in comparison with the other zones, so zone number two has the most oppressive influence on the tourist activities. In one of the next phases of the project a methodology of beach protection for the Cuban engineers is created, which can be used to solve other erosion problems. The zone from Calle 20 to Calle 37 suffers from multiple causes of erosion; that is why the problem in this zone is more complex than in the other zones and therefore more interesting to come up with a solution for it.
7.2 Situation description of critical zone Calle 20-37

As mentioned, the chosen critical zone is characterized by the presence of many structures in the dunes and on the beach. Its total length is 1500 m. In Figure 7-3, a detailed map of a big part of the zone is reflected.

![Detailed map of Calle 20-37](image)

**Figure 7-3 Detailed map of Calle 20-37**

It is clearly visible that on some places the coastline is very close to the structures. The sea is closest to the structures in the eastern part, near hotel Herradura; during high water only one meter of beach is left here. Four large commercial buildings can be distinguished: two hotels (Villa Caribe and Herradura), a restaurant (Casa de la miel la Colmena) and a policlinic. The rest of the buildings are smaller houses, of which some are rented to tourists. Most of the buildings have a terrace at seaside, ending in a vertical seawall. See Figure 7-4.
Small rocky terraces are present on some parts of the beach, just into the sea. These rocky terraces could not only play a role in the erosion, they are also very uncomfortable for people that want to go into the sea.

The mean beach profile of the critical zone Calle 23-37 can be found in the Appendix 2 (Profile section 3).

Several sand samples have been taken cross-shore near Calle 23 to determine the sand characteristics, the results of that were shown in Table 3-3. The sand characteristics are assumed to be the same in the whole critical zone.
7.3 Quantification of the erosion in the critical zone

In this Paragraph, the sediment transport in the critical zone is quantified. First, the longshore transport is considered, and then the cross-shore transport of sediment. At last, also the erosion in the critical zone due to sea level rise is considered.

7.3.1 Longshore transport in the critical zone

The values for the longshore sediment transport were calculated for the critical zone between Calle 20 and 37. The average values were taken from a run of 50 years, with UNIBEST. This is done in order to show the future development of the coastline if no erosion prevention is done.

The most important data are given below.

Regression of the coastline
A run was done for 50 years and an annual regression of the coastline was calculated.

![Change of coastline annually between Calle 23 and 37](image)

Figure 7-5 The annual change of the coastline from Calle 20 to 37

The beach erodes which causes regression of the coastline. The maximum regression is 1.45 m annually and the average regression at this stretch is 0.78 m annually.

Volumes of sediment eroded
The total volume lost along this stretch annually is: 16.320 m$^3$.

### 7.3.2 Cross-shore transport in the critical zone

In this paragraph an estimation is made for the cross-shore sediment transport in the chosen critical zone. At first, some theory will be given about the cross-shore sediment transport phenomena$^1$ $^2$. Secondly the model is described which is used to calculate the potential amount of transported sediment in the cross-shore profile.

#### 7.3.2.1 Theory of Cross-shore transport

The general shape of a coastal profile is the result of a dynamic equilibrium in the cross-shore direction. Such equilibrium can be characterized by its slope. This slope depends on the wave height, the grain size and the distance from the shore. Thus, the profile changes under influence of changes in these parameters, sometimes giving the impression erosion has occurred. But as theoretically no sand is permanently lost from the cross section, the original condition theoretically is restored by nature in the long run. In practice however, cross-shore transport gradients may occur due to for example offshore bars, causing losses of sand in the cross section. It is also possible that storm surges follow each other so short that the beach does not get sufficient time to re-establish.

Cross-shore transport is generally caused by the orbital velocities and by the undertow. Gravity also plays a role. Gravity is the most obvious destructive force, acting downslope and in a generally seaward direction for a monotonic profile. However, for the case of a barred profile, gravity can act in the shoreward direction over portions of the profile. Gravity tends to "smooth" any irregularities that occur in the profile. If gravity was the only force acting, the only possible equilibrium profile would be horizontal and sandy beaches as known would not exist. It should be recognized, however, that gravity may also serve as a stabilizing force, since sediment particles cannot be mobilized from the bed unless: upward-directed forces associated with fluid turbulence can exceed the submerged weight of the sediment, and/or slope-parallel fluid shear forces can exceed the frictional resistance of sediment. Also, as noted, gravity causes suspended sediment to settle out of the water column, with fall velocity ($W$), which may cause suspended sediment to move

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$^1$ Book: Coastal Engineering (Volume 2), ir. E.T.J.M. van der Velden, TU Delft
$^2$ Coastal Engineering Manual, (CEM)
shoreward if not suspended too high in the water column. Cross-shore transport is often a combination of bottom transport and suspended transport.

Cross-shore transport gradient can occur due to undertow. The shoreward discharge caused by the waves must be compensated by a current in offshore direction. While the shoreward discharge lies near the mean water surface, the return current has its maximum near the bed. This circulating current with its offshore-directed flow near the bed is called the undertow. The undertow is concentrated in the surf zone, partly because outside the surf zone no surface rollers transport water towards the coast, and partly because the weak energy dissipation occurring mainly in the near-bed wave boundary layer does not cause shear stresses outside the wave boundary layer.

It is well-known that wave propagation towards the shore causes a shoreward flux of linear momentum (Longuet-Higgins and Stewart 1964). When waves break, the momentum is transferred to the water column, resulting in a shoreward-directed thrust and thus a wave-induced setup within the surf zone, the gradient of which is proportional to the local bottom slope. This momentum is distributed over depth, as shown in Figure 7-6. In shallow water, the linear water wave theory predicts that one-third of the momentum flux originates between the trough and crest levels and has its centroid at the mean water level. The remaining two-thirds originate between the bottom and the mean water level, is uniformly distributed over this dimension, and thus has its centroid at the mid-depth of the water column. Because of the contribution at the free surface, breaking waves induce an equivalent shear force on the water surface. This causes a seaward bottom shear stress within the breaking zone. The bottom shear stress is dependent on the rate of energy dissipation. This effective shear force due to momentum transfer must be balanced by the bottom shear stress and the pressure forces due to the slope of the water surface.

![Figure 7-6 Distribution over depth of the momentum flux of the onshore component](image-url)
Often during major storm events, strong onshore winds will be present in the vicinity of the shoreline. These winds cause a shoreward-directed surface flow and a seaward-directed bottom flow, as shown in Figure 7-7. Of course, seaward-directed winds would cause shoreward-directed bottom velocities and thus constructive forces. Thus, landward- and seaward-directed winds result in destructive and constructive forces, respectively.

![Figure 7-7 Bottom stresses caused by winds](image)

The cross-shore transport calculations are made in a spreadsheet program, but first the used model will be described.

### 7.3.2.2 Used model

A simple analytical model for predicting dynamic profile response during storms is the so-called Convolution Method of Kriebel and Dean (1993). This method is based on the observation that beaches tend to respond toward a new equilibrium exponentially over time. For laboratory conditions, where a beach is suddenly subjected to steady wave action, the time-dependent shoreline response \( R(t) \) may be approximated by the form:

\[
R(t) = R_e \left( 1 - e^{-\frac{t}{T_s}} \right)
\]  
(Formula 7.1)

where \( R_e \) is the equilibrium beach response and \( T_s \) is the characteristic time-scale of the system. An exponential response of this kind has been observed in wave tank...

A more general result for the dynamic erosion response may be obtained by noting that Formula 7.1 suggests that the rate of profile response is proportional to the difference between the instantaneous profile form and the ultimate equilibrium form. An approximate differential equation governing the profile response to time-dependent variations in water level may be assumed in the form:

\[
\frac{dR(t)}{dt} = \frac{1}{T_s} \left[ R_{\infty} f(t) - R(t) \right]
\]  
(Formula 7.2)

where \( f(t) \) represents a unit-amplitude function of time that describes the storm surge hydrograph, while \( R_{\infty} \) represents the equilibrium beach response for the peak water level. The general solution to this system may be expressed as a convolution integral as:

\[
R(t) = \frac{R_{\infty}}{T_s} \int_0^t f(\tau) \cdot e^{-\frac{(t-\tau)}{T_s}} \, d\tau
\]  
(Formula 7.3)

As a result, several important characteristics of dynamic beach profile response are evident. First, a beach has a certain "memory," so that the beach response at any time is dependent on the forcing conditions applied over some preceding time period. As a result, the beach response will lag behind the erosion forcing. In addition, because of the exponential response characteristics of the beach system, the beach response will be damped so that the actual maximum response will be less than the erosion potential of the system.

A useful application of the convolution method is to analyze the erosion associated with an idealized storm surge hydrograph. Consider the case where the storm surge is approximated by the function:

\[
S(t) = S_{\text{max}} \sin(\pi t/T) = S f(t)
\]  
(Formula 7.4)

with \( \pi = \pi / T_0 \) and where \( T_0 \) is the total storm surge duration. The maximum storm surge level \( S_{\text{max}} \) would be used to determine the maximum potential erosion \( R_{\infty} \) according to Formula 7.5 developed in the section below. As shown by Kriebel and Dean (1993), solution of the convolution integral in Formula 7.3, with the unit-
amplitude forcing term \( f(t) \) equal to the sine-squared function, gives the following time-dependent erosion response:

\[
\frac{R(t)}{R_\infty} = \frac{1}{2} \left\{ 1 - \frac{\beta^2}{1 - \beta^2} e^{-\frac{2\sigma t}{\beta}} - \frac{1}{1 + \beta^2} \left[ \cos(2\sigma t) + \sin(2\sigma t) \right] \right\} \quad \text{(Formula 7.5)}
\]

where \( \beta \) is the ratio of the erosion time scale to the storm duration, which is given as \( \beta = 2nT_d/T_0 \). A long storm corresponds with small value \( \beta \) (for example \( \beta = 0.76 \)). In general the role of storm duration in determining the maximum erosion response is such that short duration storms may only achieve a small percentage of their potential equilibrium response.

The magnitude of the beach response from the sine-squared storm surge can be summarized in terms of the expected maximum dynamic erosion relative to the potential static or equilibrium response. In general, short-duration storms will only cause a erosion which is just 20 to 40 percent of the maximum potential erosion. For long-duration storms, the maximum erosion may be from 40 to 90 percent of the maximum potential erosion. When the storm duration is equal to the erosion time scale, \( (\beta = 2n) \), the dynamic erosion response is only 36 percent of the static response. It must be mentioned that the calculation is highly sensitive for the value of the beach slope. It is even possible that a calculation indicated accretion instead of erosion.

The time scale of dynamic profile response \( T_\delta \) has not been as widely considered in coastal engineering as the equilibrium erosion \( R_\infty \) and, thus far, the time scale has not been derived analytically. As a result, empirical descriptions of the time scale are required. These have been developed from results of the numerical erosion model of Kriebel (1986, 1990) for various combinations of profile geometry and breaking wave conditions. From these numerical tests, it was found that the time scale was approximately independent of the storm surge level, but varied strongly with sediment size (through the \( A \) parameter) and breaking wave height, and varied less significantly as a function of beach profile geometry. Numerical results were analyzed by dimensional analysis to arrive at the following empirical relationship:

\[
T_\delta = 320 \frac{H_s^3}{\sqrt{g \cdot A}} \left( 1 + \frac{h_b}{B} + \frac{m_w W_b}{h_b} \right) \quad \text{(Formula 7.6)}
\]
Kriebel and Dean (1993) considered both profiles with a vertical face at the water and profiles with a sloping beach face. They showed that by accounting for the small wedge-shaped sand volume offshore of the breaking depth, somewhat improved expressions could be developed for the potential beach recession due to elevated water levels. As shown by Kriebel and Dean (1993), the general result for equilibrium recession due to a storm surge level $S$ is given as

$$R_e = S \frac{W_b - h_b}{B + h_b - \frac{S}{2}}$$

(Formula 7.7)

where $m_b$ is the slope of the beach profile at the waterline. This slope is joined to the concave equilibrium profile at a depth where the slope of the equilibrium profile is equal to $m_0$. As a result, the surf zone width can be shown to be equal to

$$W_b = \left( \frac{h_b}{A} \right)^{\frac{3}{2}}$$

(Formula 7.8)

where $A$ is a sediment scale parameter.

For engineering application, it is also of interest to compute the volume of sand eroded between the initial and final profiles per unit length of beach. For the case with a sloping beach face, the volume eroded from the berm above the initial still-water level due to a storm surge level $S$ is given by:

$$V_e = R_e \cdot B + \frac{S^2}{2m_b} - 2 \frac{S^5}{5 \frac{S}{A}^3}$$

(Formula 7.9)

### 7.3.2.3 Calculations

In this Paragraph some calculations are made. Cross-shore transport is mostly occurring during stormy conditions so most of the calculations are made with extreme values. The first a calculation is with the input parameters belonging to the most severe storm of the last years and the second is with information from the Global Wave statistics.
7.3.2.3.1 Hurricane Michelle

Hurricane, Michelle, struck Cuba in 2001 and caused a lot of erosion. To give an estimation of the devastating consequences on the beach a calculation is made for this storm.

First the input parameters of the storm Michelle are given.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB (m)</td>
<td>6,64</td>
</tr>
<tr>
<td>$H_d$ (m)</td>
<td>8.29</td>
</tr>
<tr>
<td>$M_0$ (-)</td>
<td>0.02</td>
</tr>
<tr>
<td>$S_{max}$ (m)</td>
<td>1.5</td>
</tr>
<tr>
<td>$T_d$ (hrs)</td>
<td>10-12</td>
</tr>
<tr>
<td>$T_0$ (s)</td>
<td>8.0</td>
</tr>
<tr>
<td>A (-)</td>
<td>0,132</td>
</tr>
</tbody>
</table>

Table 7-1 Input parameters from Hurricane "Michelle"

Most of the parameters (HB, $S_{max}$, $T_d$, $T_v$, $T_0$) were obtained from a metrological report\(^1\). The information from this report was used to calculate the breaking depth with CRESS.

After this calculation all the parameters were known to calculate the regression of the coast and the amount of transported sediment. A trend line is plotted in the profile (see Appendix 15) to calculate the average beach slope. The results from the computation will be shown in the next Paragraph, but are also presented in Appendix 15.

7.3.2.3.2 Calculations with waves from the Global Wave Statistics

Due to a lack of sufficient information about storms, some calculations were made with the wind conditions of the Global Wave Statistics. From the statistics the occurrence of a wave height could be computed. Occurrence times the number of hours per year results in the total durations of a wind condition. Which means, the wind blows X hours from a certain direction and causes certain wave conditions, on deep water. This does not mean that the wind blows X hours from a certain direction in one time, it is only noticed that this wind occurs this much during one year. It is

\(^1\) Estudio Hidrometeorologico Marino
therefore a big assumption to say that the calculated wind condition appears only one time with this X duration.
The mean duration of a storm or cold front is about 6-8 hours. From every wind direction (West, Northwest, North and Northeast), one significant wind condition is taken, which occurs approximately 6-8 hours per year. In the computation the duration of a storm is needed. Before the calculation can be made the other parameters (HB and H_d) have to be calculated with CRESS.
The sea level elevation (S_max) is assumed to be 0,5m.
As every relevant parameter is known, the amount of cross-shore sediment transport can be calculated. See Appendix 15 for the chosen input parameters and the results.

7.3.2.4 Results
In this Paragraph the results of the several calculations are given. In respective order: hurricane “Michelle” and secondly the calculations with waves derived from the Global wave statistics.

7.3.2.4.1 Results of the ‘Michelle’ calculation:

From the calculation follows a regression of about 5m and a total sediment volume of approximately 42m³ per unit beach length disappeared during the hurricane. See Appendix 15.

In comparison with the measurements from the Institute of Oceanology these values are quite accurate. The measurements showed on several places a regression of 5-6 meters.

The institute had also some profiles before and after the storm which show some accretion at several points in the critical zone. This can be explained by the different profiles in the zone. It is normal that during a storm a mild sloped beach shows some accretion. In the model only mean profile is taken into account that is why in this calculation only erosion is detected.

7.3.2.4.2 Results of the other calculation with GWS

As mentioned (Paragraph 7.3.2.2), the used model is valid in case of a sloping beach. In this case the bottom slope is mild; therefore one should not be surprised if the outcomes do not show the expected results (accretion instead of erosion). It depends on the wave condition if erosion or accretion occurs.
Considering the results of the calculation (see Appendix 15), the outcomes of west and northeastern directions show some negative values for the regression of the coast. This indicates that the parameters have exceeded the validity boundary of the model. For the other wind directions the results show positive values, except for the transported sediment. On first hand the values of the regression values look realistic, but because of a negative value for the North Western direction, the computation should be neglected. Therefore the only valid calculation is the one of the Northern direction. With a breaking depth of 7.1m and a breaking wave height of 5.8m the regression of the coast is slightly more than half a meter. The amount of eroded sand is calculated on 8,70m³ per unit beach length. The total amount of cross-shore sediment transport throughout the critical zone per year is therefore; 8,70m³/m * 900m = 38,000m³.

7.3.2.5 Evaluation of the model

It has already been mentioned before; the model is made for computations with a sloping beach and stormy conditions. The mild beach slope in this case is responsible for the high sensitiveness of the input parameters. Together with the breaking depth, the beach slope influences the maximum regression mostly. It is possible that the input parameters cause a negative maximum regression of the coast and this can not be compensated with the sea level elevation. This is not acceptable, because the model attempts to calculate the regression, not accretion. The result of interest is the actual response of the coast line (and the amount of eroded sediment), which is determined by calculating the rate between response of the coast line and the maximum regression. This rate is always positive. Therefore if the maximum regression has got a negative value the response of the coastline will also be negative. This may lead to the wrong conclusion that accretion occurs.

The beach slope has got a fixed value that is why the sign of the maximum regression depends mostly on the value of the breaking depth. After a sensitivity analyses, it was clear that the model gives postive results for the maximum regression if the breaking depth is more than 5.8m. A breaking depth of this value corresponds to large wave heights (on deep water), which mostly occur during stormy conditions (hurricanes and cold fronts). For that reason the calculations with the parameters derived from the Global Wave Statistics do not give satisfying results, because the wave climates from the several directions cause lower waves that break closer to the coast.

So, the used model is only valid for computations with stormy conditions (hₚ>5.8m), considering a beach slope of 1:50. The calculated regression of the coast of 5.8m
during hurricane "Michelle" is realistic value. The amount of eroded sand of 38,000 m$^3$ is a slight overestimation.
7.3.3 Erosion due to sea level rise in the critical zone

To determine the erosion by global sea level rise in the critical zone, BRUUN’s rule (Formula 6.1) can be used again. But, as the beach profile in this zone differs from the mean profile used in the calculation for the whole peninsula, the distance out to the closure depth \( x_c \) in the critical zone has to be determined.

This is done with the profile of this section, shown in Figure 7-8. With a closure depth of 11.2m, an \( x_c \) of 1040m is found.

![Profile Section 3](image)

Figure 7-8 Closure depth and width of the active profile in the critical zone

This results in a recession of the beach of 0.2 m/year.

The volume of eroded sand can be determined by the simplification of BRUUN’s profile (see Figure 6-5). This results in an eroded volume of 1.42m³/m/year. Over the length of critical zone 3 (1500m) this is 2130 m³/year.
7.4 Summary

Based upon the calculations with the programs UNIBEST\(^1\) and CRESS there are three critical zones distinguished where the most erosion occurs. From these three zones, one zone is chosen. This is the critical zone between Calle 20 and 37 in the old town of Varadero. Many buildings are present on the dunes and beach. Solutions will be proposed only for this zone in the next phases of the project.

The coastal retraction due to longshore transport varies throughout the critical zone from 0.78 to 1.45 meters per year. The total amount of sand that is lost in the critical zone due to longshore transport is 16.320\(\text{m}^3\)/year.

The computation made with the Cross-shore model of Kriedel and Dean shows a coastal retraction of 5.8m per storm. This retraction is based on the input parameters of the hurricane “Michelle”. The total amount of eroded sand is determined on 38.000\(\text{m}^3\). This amount a slight overestimation.

The used model is only valid for computations with stormy conditions (\(h_o>5,8\text{m}\)), considering a beach slope of 1:50. This means that the model is only valid for high waves, which break far from the coast.

The coastal retreat due to sea level rise is 0.20 meters per year. This leads to a total amount of sand of 1420\(\text{m}^3\) that is eroded each year.

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\(^1\) Modeling program from WL Hydraulics Delft (The Netherlands)
8 List of requirements

In the former chapters the causes of the erosion are determined and a most critical zone of the peninsula is selected. In this chapter design criteria for solutions for the erosion problems are presented. First the boundary conditions from the Hicacos Peninsula and the assumptions made are given. From this list of requirements the bill of demands is obtained.

8.1 Boundary conditions

8.1.1 Technical

TB1 The future coastline has to be extended and fixed
TB2 Measures to prevent any further regression of the coastline have to be structural
TB3 Nourished sands should have no significant difference with the original sands
TB4 The equipment in Cuba for construction works is limited
TB5 The lifespan of hard measures should satisfy the international demands
TB6 Measures taken may not cause new problems
TB7 Hard solutions have to be designed to withstand design wave conditions
TB8 Offshore structures are to be built in shallow water to avoid the need of large structures
TB10 West of Hotel Oasis the coast consists of low coral cliffs meaning hard rock without any beaches in between (this goes for the whole stretch from Hotel Oasis to the Bay of Matanzas)
TB11 There are two smaller (10 and 40 meter) groins present near Hotel Oasis
TB12 A breakwater is present at both sides of the mouth of the Paso Malo
TB13 The coast consist of sands between Hotel Oasis and Palacio de la Rumba (PdIR)
TB14 From PdIR to Punta Chapelin the coast consists of rocky cliffs
TB15 From Punta Chapelin to Punta Frances the coast consists of sand
TB16 Between Calle 23 and 37 buildings are on the dunes close (varying from 1,5 to 10 meters) to the shore line.
8.1.2 Functional

FB1 A minimum beach area per tourist is required
FB2 The slope of the dry beach may not be uncomfortable
FB3 The accessibility of the beach should not be hindered
FB4 The beach should be accessible for vehicles in longshore direction
FB5a The main tourist season is from September till April
FB5b Storms occur from September till November
FB6 Any coastal defense measures may not form a danger to structures or persons

8.1.3 Environmental

EnB1 Flora and fauna in the coastal area may not experience severe damage due to any coastal defense measures

8.1.4 Economic

EcB1 Funds for beach protection are limited in Cuba
EcB2 Local equipment and materials are less expensive than from other countries
EcB3 No funds are available to relocate the existing hotels and other buildings in Historic Varadero

8.1.5 Juridical

JB1 Coastal defense measures have to obey the Decreto Ley (the Cuban Law on coastal zones)
JB2 No sand extraction from the sea if it effects the dynamic zone

8.1.6 Cultural and historic

CB1 Structures for coastal defense may not rise above the water level
CB2 Some buildings have historical value

8.1.7 Assumptions

A1 The sand on all beaches has the same characteristics
A2 Waves from west, northwest, north and northeast are taken into account
A3 From the waves a mean period for each direction is taken into account
A4 Where the Decreto Ley gives no information the Dutch standards are used
8.2 Bill of demands

8.2.1 Technical

TD1 The present coastline has to be fixed 15 m seawards of its present location
TD2 In case of soft solutions a nourishment plan with a return period of 5 years has to be worked out
TD3 The nourished sands should have approximately the same color and mean diameter as the original sands
TD4 Construction has to be able to be done with Cuban equipment
TD5 The lifespan of hard measures has to be 50 years
TD6 No places on the Peninsula may suffer from any erosion problems due to measures taken at another place on the Hicacos Peninsula
TD7 Hard solutions have to be designed for a wave with characteristics $H_s = 5.24$ m and $T = 8.15$ s (for calculation of this wave see Appendix 16).

8.2.2 Functional

FD1 The minimum mean beach area per tourist has to be 10 m$^2$
FD2 The maximum dry beach slope is 5 %
FD3 Every Calle should keep access to the beach
FD4 A passage of 3.5 m width should remain in cross shore direction on the dry beach
FD5 Offshore construction is not possible from September till November and should take place from May till August as much as possible

8.2.3 Environmental

EnD1a Turbidity of the sea caused by coastal defense has to be avoided
EnD1b Vegetation on the dunes should be preserved as much as possible

8.2.4 Economic

EcD1a The total costs should be minimalized
EcD1b The coastal defense measures should be economically feasible
EcD2 Local equipment and materials should be used as much as possible
EcD3 The existing buildings on the dunes can not be relocated
8.2.5 Juridical

JD1a Where low rocky terraces are concerned no structures are to be built within 20 meters landwards (from the start of vegetation on the beach or dune)

JD1b Where rocky cliffs are concerned no structures are to be built within 20 meters landwards from the top of rocky cliffs

JD1c Where sandy coasts are concerned no structures are to be built within 40 meters landwards (from the start of vegetation on the beach or dune)

JD1d Where mangroves are concerned no structures are to be built within the mangroves (the furthest penetration land inwards of the mangroves forms the boundary)

8.2.6 Cultural and historic

CD1 The crest of coastal defense structures may not be higher then MLW -1.0 m

CD2 No historical monuments should be destroyed
9 Alternatives

In the chapter 7 the zones are determined where the erosion problems are most severe, and a choice is made for the most critical zone Calle 23 -37. A list of requirements is made to determine the design criteria for solutions for the problems. In this chapter alternatives for solutions will be proposed and explained.

9.1 Introduction

The purpose of this chapter is to determine several alternatives to protect the beach in the critical zone Calle 23 – 37 from erosion. These alternatives can be divided in four different types of solution. In this group different alternatives are generated and explained. Estimations have been done about location, dimension and construction, to get a clear idea of the alternative. The alternatives are:

Hard solutions (Sub-chapter 9.2);
  • AH1  Groin
  • AH2  Offshore emerged Breakwater
  •  - AH3  Offshore submerged Breakwater
  • AH4  Fishtailed Breakwater
  • AH5  Extension of the Paso Malo Breakwater

Soft solutions (Sub-chapter 9.3);
  • AS1  Nourishment
  • AS2  Maintenance

Other type of solutions, non-engineering solutions are presented in Paragraph 9.4.

The alternatives are evaluated in a Multi Criteria Analysis (Paragraph 9.5) this analysis takes into account the requirements to be fulfilled and therefore pointing out the best solutions for the area.

9.2 Hard solutions
Hard solutions serve the purpose of providing quiet water or trapping the sediment transport. Many different types of hard solutions exist, but in this chapter not all these types are described. The alternatives proposed are the ones that fulfill the most important function for this investigation: the protection of the shore from erosion. In this Paragraph only estimates on location, dimension, and construction are given. The data on dimensions and construction are estimated with the use of the manual on the use of rock in hydraulic engineering.\(^1\)

### 9.2.1 Groin field

A groin is a relatively short structure running seaward from the beach head. The primary function is to interrupt the longshore transport of sediment in order to build or retain higher beach levels and thereby protecting the existing coast. An individual groin interrupts this transport forming accretion of the beach on its up drift side, and erosion down drift. The purpose of a groin field (series of groins) is to divide the shoreline into short sections that can re-orientate themselves with respect to the incoming waves. Groins will change the longshore sediment transport rates. This will result in accretion up drift of the groins and within the groin field and erosion down drift.

*Location (Figure 9-1):*

The groins are attached to the shore in the critical zone.

![Diagram of a groin field](image)

*Figure 9-1 location groin field*

*Dimension:*

The length of a groin is in the order of 100 m. With rock groins a spacing/length ratio of 2:1 is a typical value. The crest height is for esthetical purposes placed on 1.5

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\(^1\) Manual on the use of rock in Hydraulic Engineering, Cur report 169
meter below M.S.L. The slope is 1:3 to reduce wave reflection that arises and the increased diffractive capability to encourage sediment to build up on the lee of the groin.

Construction:
The bastion groin will be made up of a single grading of armour stone, with the larger rocks set to one side during construction for placing on the cover part of the groin, thus giving additional protection. The structure is founded on a modest bedding stone layer.

Comments:
The groin field only protects against the longshore sediment erosion while no cross-shore protection is given. The groin will cause erosion on the lee side, on the west of the critical zone. This might not be tolerated and therefore the construction of more groins on lee side forming a larger groin field should be taken in consideration. For a beach with a small particle size of sand, such as the case on the peninsula, the groin field that will attempt to control the sediment movement will only be partly effective. The groin field can be easy constructed as supply of material can come from the land.

9.2.2 Offshore emerged Breakwater

Rather than physically trapping the sediment by the longstop method, offshore or detached breakwaters operate causing a zone of reduced wave energy behind them. As waves pass the breakwater they diffract as they travel towards the shore. The diffracted waves change the beach shape from a relatively straight shore to a curved shoreline with either a salient (accretion that does not reach the structure) or a tombolo (accretion that does reach the structure).

Location (Figure 9-2):
An offshore breakwater is situated roughly at the beginning of the breaker zone, which will allow it to influence about the inner half of the inner zone. Or at least 3 wave lengths. Because placing it at the beginning of the breaker zone at a depth of 11.5 m would lead to a gigantic structure. That is why in this case the breakwater is placed at approximately 200-300 m from the shore.
Figure 9-2 Location offshore breakwater

**Dimension:**
The length of the breakwater is equal to the distance from the shore in this case 200-300 m. The crest height of the breakwater can be about 1 meter above H.S.L, allowing most waves to break. The outer face of the breakwater has a slope greater than 1:4 to reduce reflective scour and increase energy dissipation. The rear face can be steeper. Special attention has to be paid to the roundhead.

**Construction:**
The offshore breakwater has a trapezoidal shape. The primary armour layer also covers the crest and part of the lee slope. The structure consists of a core of quarry run and is protected by primary armour at the seaward slope, on the crest, and on part of the leeside slope. A filter layer or secondary armour layer may be needed between core and primary armour, depending on filter requirements and the required wave protection of the core during construction. A filter layer or secondary armour layer can be required between the structure and the sea bed.

**Comments:**
An offshore breakwater can be used to reduce the wave climate behind it and thus accelerating the beach accretion behind it. It can be well used in areas with substantial cross-shore transport. Offshore breakwaters have been used with most success on coastlines where the tidal range is negligible or small as in the case of the peninsula. Particular useful to protect a beach where erosion is occurring because net transport rate is higher than elsewhere. The emerged breakwater can be seen from the shore. ‘Beneficial’ onshore transport is arrested as well. The current behind offshore breakwaters can be dangerous to swimmers.
9.2.3 Offshore submerged breakwater

A submerged breakwater can be described as an offshore breakwater, fulfilling the same functions. But the structure cannot be seen from the beach. A statistically stable armour layer can cover the core, or alternatively (in the reef type breakwater) the core is allowed to reshape under the wave conditions.

Location (Figure 9-2):
Same location as the emerged breakwater

Dimension:
Same dimensions as the emerged breakwater, only the crest height differs here and is approximately 1.5 m below MSL.

Construction:
The construction of the submerged breakwater is based on the same construction principles as the emerged breakwater, but since wave energy is transmitted over the breakwater the armour has to be extended to the lee-side as well. Other designing considerations do not differ much from the emerged breakwater.

Comments:
The comments for the emerged breakwater are applicable to this solution as well, but in this case the breakwater is not seen from the shore.

9.2.4 Fishtailed Breakwater

The concept of the fishtailed breakwater is to combine the beneficial effects of the groin, offshore breakwater and tombolo to reduce the undesirable effects of separate structures. Two breakwater arms act as breakwaters to dissipate the wave energy. While the attached arm acts as interceptor of the longshore drift. Thus the up drift beach is formed by normal accretion processes associated with a groin while the down drift beach is formed by processes associated with an offshore breakwater.

Location (Figure 9-3):
The location of this breakwater will be in the middle of the critical zone. The up drift outer (eastern) arm is orientated towards the main driving force of the sediment transport, the wind from the N-NE. Its function is to intercept the longshore current.
The down drift outer (western) arm is orientated towards the most severe storm attacks from the NW, to allow the waves to break on the arm.

![Figure 9-3 Location fishtailed breakwaters](image)

**Dimension:**
The land link of the breakwater extends 200-300 m from the shoreline. Side slopes of the link are set on 1:2 as in groins. The length of the down and up drift outer arm is approximately 200 m. With slopes of 1:4 for the outer face exposed to the storm.

**Construction:**
The construction of a fishtailed breakwater involves a combination of the concepts for groins and offshore breakwaters.

**Comments:**
The combination of breakwater and groin causes an accretion on both sides of the breakwater, so no erosion of the direct surroundings will occur. The fishtailed breakwater is visually not a very attractive solution.

**9.2.5 Extension of the Paso Malo breakwater**

An extension of the eastern Paso Malo breakwater will totally interrupt the longshore transport, thus leading to accretion of the shore east of the breakwaters.

**Location (Figure 9.4):**
The extension will of course be at the current location, with a direction perpendicular to the coastline.
Figure 9-4 Extension of the Paso Malo breakwater

Dimension:
A length of 500 meter seaward keeps 100% of the sediment transport. The slope on
down drift side is 1:3 to reduce wave reflection that arises and the increased
diffractive capability to encourage sediment to build up on the lee side.

Construction:
A caisson type structure can be used, where caissons are placed on a foundation.
Special attention has to be paid to the foundation of the caissons.

Comments:
Increase of erosion on the lee side will occur.
The extension of the Paso Malo breakwater was an alternative that was explicitly
asked for us to look at by our tutor at CUJAE. Therefore the extension of the
breakwater was modeled in UNIBEST. The result is that no significant positive
influence can be achieved for the critical zone between Calle 20 and 37 by extension
of the breakwater. The computations for this result are given in Appendix 17.
9.3 Soft solutions

9.3.1 Nourishment

Nourishment is the process involving extraction of sand ('borrowed') from a place outside of the dynamic zone, and added on the place where it is needed. There are many different types of nourishment, characterized by the location in the coastal zone where the nourishment is executed. In this Paragraph, only the types of nourishment that are applicable on the peninsula are considered. The possible locations of the nourishment are:

- Nourishment on the foreshore and beach of Calle 20 - 37
- Nourishment on the foreshore and beach east of Calle 20 – 37
- Combination of nourishment on foreshore and dunes of Calle 20 - 37

The sand will be borrowed from the extraction zone used in previous nourishing programs on the peninsula, just south of Cayo Mono, about 10 kilometers from the critical zone. Estimations by CISMA indicate a total amount of 5,000,000 m³ that can be extracted from this site. The mean diameter of this sand is 0.38mm.

9.3.1.1 Alternative 1, Nourishment on foreshore and beach Calle 20-37

Location (Figure 9-5):
In this alternative, the nourished sand will be put directly onto the foreshore of Calle 20 - 37. Both beach as foreshore are nourished. See Figure 9-6.
**Dimension:**

Only to extend beach size for fifteen meters, about 250,000 m\(^3\) of sand has to be nourished in the critical zone. Because the beach will erode directly after the nourishment and the demand is that in five years the coastline is still increased 15 meters seaward, more sand has to be nourished. Also, other losses occur due to for example different grain sizes. In this first estimation losses are estimated\(^1\) on 50%. So, about 325,000m\(^3\) has to be nourished. A cross-section of this nourishment is reflected in Figure 9-6.

![Figure 9-6 Cross-section of nourishment alternative 1](image)

**Construction:**

A nourishment on the foreshore is usually done by trailing suction hopper dredgers. If there is enough depth it will be done by dumping, in shallower water and on the beach by pressing or booming. The spout mouth then is placed on a hopper dredger or a pontoon that is connected with a dredger.

**Comments:**

After the nourishment, the beach immediately will be wider and the area available for recreational activities is thus extended very fast. The nourished sand will immediately be under the influence of waves, decreasing the lifespan of the nourishment.

---

\(^1\) With the use of 'Handboek Zandsuppleties', Rijkswaterstaat, 1988
9.3.1.2 Alternative 2, Nourishment on foreshore and beach east of Calle 20-37

Location (Figure 9-7):
In this alternative the sand is nourished on the foreshore and beach east of Calle 20 – 37 in a local extension of the coast. The extension is slowly eroded by wave action giving a continuous input of sand to the critical zone.

![Figure 9-7 Location of the nourishment, alternative 2](image)

Dimension:
The total loss of sediment in the critical zone is about 16000 m$^3$/year. This every year loss has to be compensated by the transport from the nourished zone. Assuming a loss in the nourished section during five year of 50%, like in alternative 1, at least 160,000m$^3$ of sand has to be nourished.

Construction:
The execution of this nourishment is the same as in alternative 1.

Comments:
The beach in the critical zone is held steady in this alternative; no bigger beach size is created. East of the critical zone, the beach area is little increased. A strong local extension of the beach is not very attractive.
If the beach width in the critical zone should be increased with 15 meters, a large extension of the coast east of Calle 20 – 37 would have to be made, and a lot more sand has to be nourished.
9.3.1.3 Alternative 3, Combination of foreshore, beach and dune nourishment Calle 20-37

Location (Figure 9-8):
In this alternative the sand is nourished onto the foreshore, the beach and the seaside of the dunes/revetments between Calle 20 - 37.

![Figure 9-8 Location of the nourishment, alternative 3]

Dimension:
About 325,000 m$^3$ of sand would have to be nourished on the foreshore and beach to guarantee that over five years the beach width in the critical zone is still increased with 15 meters. The amount of sand nourished on the dunes to protect the beach against storm surges or in front of the sea wall has to be add up to this, resulting in about 425,000 m$^3$ of sand that would have to be nourished.

Construction:
The construction on the foreshore and beach is the same as in the other alternatives. The nourishment on the dunes can be done with hydraulic sand transport. A press quay is needed, what can be built and maintained by a bulldozer.

Comments:
Dunes are not everywhere present in the critical zone, so extra sand should be nourished in front of the revetments, creating small artificial dunes. Big dunes are not advisable in front of the revetments from an esthetical point of view. The beach width has increased much after the nourishment. A negative aspect of the nourishment of the dunes and in front of the revetments is the decrease of beach size and the visual and physical obstruction in the dunes. These aspects have a negative influence on the recreational activities. A positive effect is the extended lifespan of the nourishment because it is more combative to storm surges.
9.3.2 Maintenance

Location (Figure 9-9):
The location of the maintenance is the whole critical zone. No extra sand is added from outside the dynamic zone; within the zone the sand is moved from the first bank to the coast.

![Figure 9-9 Location of the maintenance](image)

Dimension:
Every year this maintenance has to be executed after the winter, to bring back the sand to the shore that is transported cross-shore. This sand is not naturally brought back to the shore, because there is no cross-shore equilibrium situation reached due to the fact that there is not enough beach left for the wind to blow back the sand. The amount of this sand depends on the number and intensity of storms, but can get up to values of 40.000m³ per year.

Construction:
The sand is extracted from the first bank with a small dredging vessel and transported to the coast with a press pipe, afterwards spread on the beach by the use of bulldozers.

Comments:
The beach width is not increased with maintenance. Also the lifespan of the maintenance is short as it has to be executed every year. Longshore sediment transport is still occurring, causing erosion and the coastline will still retreat. Only cross-shore sediment losses of the beach are compensated. Nourishment or other alternatives are still needed to prevent structural erosion.
9.4 Other types of solutions

The solutions described in this Paragraph are beyond the scope of the investigation for this research as they are not seen as engineering solutions. Therefore they are not taken into account in the MCA. But to resolve the erosion problems on the peninsula, these measures can attribute to an optimal solution. The proposed solutions can be seen as recommendations for a longterm solution.

9.4.1 Demolition of existing structures on the dune

As concluded in Paragraph 4.5.1 the construction of hotels and houses on the dunes and the destruction of natural vegetation on the dunes have disturbed the dune-beach system seriously and play thereby a significant role in the erosion of the peninsula. This is especially the case in the critical section. Demolition of the buildings on the beach and restoring the dunes eliminates fixed obstacles in the beach profile and expands the dynamic zone land inwards.

If demolition of structures on the dune is the case, the dune must be restored in order to supply the beach with sand during erosive storm events. So a new dune has to be constructed, or the existing dune has to be repaired. This can be done using earth-moving equipment (shovels and bulldozers).

In the attempt to restore a dune-beach system it is also important to ensure that indigenous vegetation (Figures 9-10 and 9-11) covers the dunes.

![Figure 9-10: Current dune vegetation in the critical zone](image)

Dune vegetation serves two functions:
• Stabilize sand deposits
• Provide a buffer that encourages deposition of wind-blown sand on the dune surface.

The solution proposed here is not really a solution from an engineering point of view but more a measure that has to be adopted in the coastal management of Varadero. Of course, it is easy to advice demolition of the structures on the dune but in practice this proves to be a complicated case in which different parties with conflicting interests play a role.

Demolition of buildings is possible but not for every structure. It is a slow process that will take time, and demolition would have to take place in phases that depend on the development of tourism constructions and the current economic-political situation. Nowadays the focus in Varadero is on expansion of the current tourism constructions not on demolition. Furthermore the much-needed income is usually obtained from the buildings that would have to be demolished.

When structures on the dune will be demolished and the dunes will be restored with vegetation, a natural dune-beach system will be present again. So after a storm, the sand that moves into the sea forming offshore bars comes from the restored dune and after the storm, the material moved offshore will return onshore, forming dry beach. Wind will blow back the dry sand inland, replenishing the dunes. This will take away the negative effects from locale cross-shore erosion in this zone.

9.4.2 Biotechnology

A somewhat unconventional solution lies in the increase of sand input by the use of biotechnology: the production of sand by the Algae Halimeda. By expanding the existing underwater fields of the Algae the sand production could be increased. It is a long-term solution in which the allocation of the fields is of essential importance, as currents to the peninsula must carry the sand produced by the ‘skeletons’ of the Algae. As this is an unconventional solution not much is known about the execution and cost of such a project.
9.5 Multi Criteria analysis

To make a founded decision about what alternatives will be worked out; all the possible solutions must be compared in a Multi Criteria Analyses (MCA). First of all the following criteria and variables are determined (Table 9-1).

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality</td>
<td>Stabilization coast line</td>
</tr>
<tr>
<td></td>
<td>Width beach</td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
</tr>
<tr>
<td></td>
<td>Reliability</td>
</tr>
<tr>
<td>Costs</td>
<td>Maintenance costs</td>
</tr>
<tr>
<td></td>
<td>Investments costs</td>
</tr>
<tr>
<td></td>
<td>Demolishing costs</td>
</tr>
<tr>
<td>Environment</td>
<td>Durability</td>
</tr>
<tr>
<td></td>
<td>Physical fit</td>
</tr>
<tr>
<td></td>
<td>Esthetics</td>
</tr>
<tr>
<td></td>
<td>Nuisance</td>
</tr>
<tr>
<td></td>
<td>Building time</td>
</tr>
<tr>
<td>Technique and carrying out</td>
<td>Lifespan</td>
</tr>
<tr>
<td></td>
<td>Presence of materials and equipment in Cuba</td>
</tr>
<tr>
<td></td>
<td>Logistic complexity</td>
</tr>
</tbody>
</table>

Table 9-1 Criteria and variables used in the MCA

Table 9-1 is explained further in Appendix 18.

In order to make a MCA, the criteria on which alternatives are compared have to be weighted to show the importance of each criterion. In Table 9-2, the criteria are compared with each other. When the criterion in the row is more important than the criterion in the column, ‘1’ is noted. If not, a ‘0’ is noted. In the last column, the total is added up. The highest total indicates the most importance, the lowest the least importance. The weight is computed by adding one to the total. By doing that, a weight of zero (indicating zero importance) is prevented.
<table>
<thead>
<tr>
<th></th>
<th>Functionality</th>
<th>Costs</th>
<th>Environment</th>
<th>Technique and carrying out</th>
<th>Total</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality</td>
<td>x</td>
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<td>1</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Costs</td>
<td>0</td>
<td>x</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Environment</td>
<td>0</td>
<td>1</td>
<td>x</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Technique and carrying out</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>x</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 9-2 Determination of weights of criteria**

Protection of the Peninsula from further erosion is one of the main goals, so it is clear why functionality scores most. The environment also is of big importance, looking at the many tourists that visit the peninsula every year for its beautiful beaches.

Now the weight of the criteria is determined, weight factors can be calculated. See Table 9-3.

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Weight factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality</td>
<td>4</td>
<td>4/10 = 0.40</td>
</tr>
<tr>
<td>Environment</td>
<td>3</td>
<td>3/10 = 0.30</td>
</tr>
<tr>
<td>Costs</td>
<td>2</td>
<td>2/10 = 0.20</td>
</tr>
<tr>
<td>Technique and carrying out</td>
<td>1</td>
<td>1/10 = 0.10</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.00</td>
</tr>
</tbody>
</table>

**Table 9-3 Weight factors for criteria**
Next, the variables of the criteria are weighted by giving each criteria a number of importance, from 1 (little importance) to 5 (high importance). After that, the variable weight factor within the criterion can be determined and the final weight factor for each variable can be calculated. See Table 9-4.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Variable</th>
<th>Number of importance</th>
<th>Variable weight factor</th>
<th>Criterion weight factor</th>
<th>Final weight factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality</td>
<td>Stabilization coast line</td>
<td>5</td>
<td>0.31</td>
<td>0.40</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Width beach</td>
<td>5</td>
<td>0.31</td>
<td>0.40</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Reliability</td>
<td>3</td>
<td>0.19</td>
<td>0.40</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td>3</td>
<td>0.19</td>
<td>0.40</td>
<td>0.08</td>
</tr>
<tr>
<td>Environment</td>
<td>Durability</td>
<td>2</td>
<td>0.12</td>
<td>0.30</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Physical fit</td>
<td>3</td>
<td>0.18</td>
<td>0.30</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Esthetics</td>
<td>5</td>
<td>0.29</td>
<td>0.30</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Nuisance</td>
<td>4</td>
<td>0.24</td>
<td>0.30</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Building time</td>
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<td>0.18</td>
<td>0.30</td>
<td>0.05</td>
</tr>
<tr>
<td>Costs</td>
<td>Maintenance costs</td>
<td>3</td>
<td>0.33</td>
<td>0.20</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Investments costs</td>
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<td>0.20</td>
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<td>Demolishing costs</td>
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<td>0.11</td>
<td>0.20</td>
<td>0.02</td>
</tr>
<tr>
<td>Technique and carrying out</td>
<td>Lifespan</td>
<td>4</td>
<td>0.33</td>
<td>0.10</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Presence of materials and equipment in Cuba</td>
<td>5</td>
<td>0.42</td>
<td>0.10</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Logistic feasibility</td>
<td>3</td>
<td>0.25</td>
<td>0.10</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 9-4 Final weight factor of the variables
The alternatives will be weighted by their score (1-5) on the variables. The score on a certain variable is multiplied by its weight factor. Afterwards, the total of this multiplication is added up and the total score of an alternative can be determined. The alternative with the highest score is the best alternative; the alternative with the lowest score is the worst.

The alternatives that are taken in consideration in this multicriteria analysis are displayed in Table 9-5.

<table>
<thead>
<tr>
<th>Alternative number</th>
<th>Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZERO</td>
<td>ZERO-alternative</td>
</tr>
<tr>
<td></td>
<td>Hard solutions</td>
</tr>
<tr>
<td>1</td>
<td>Groins</td>
</tr>
<tr>
<td>2</td>
<td>Offshore emerged breakwater</td>
</tr>
<tr>
<td>3</td>
<td>Offshore submerged breakwater</td>
</tr>
<tr>
<td>4</td>
<td>Fishtailed breakwater</td>
</tr>
<tr>
<td>5</td>
<td>Extension of Paso Malo breakwater</td>
</tr>
<tr>
<td></td>
<td>Soft solutions</td>
</tr>
<tr>
<td>1</td>
<td>Nourishment on the foreshore of Calle 20 – 37</td>
</tr>
<tr>
<td>2</td>
<td>Nourishment on the foreshore east of Calle 20-37</td>
</tr>
<tr>
<td>3</td>
<td>Nourishment on the foreshore and dunes of Calle 20 -37</td>
</tr>
<tr>
<td>4</td>
<td>Maintenance</td>
</tr>
</tbody>
</table>

Table 9-5 Alternative taken in consideration of MCA

As one can see, to compare the alternatives to the current situation the zero-alternative (nothing is done) is also taken in account in this MCA. The results of the MCA are shown in Table 9-6.
<table>
<thead>
<tr>
<th>Alternative</th>
<th>Stabilisation Coast Line</th>
<th>Width beach</th>
<th>Maintenance</th>
<th>Reliability</th>
<th>Durability</th>
<th>Physical fit</th>
<th>Aesthetics</th>
<th>Nuisance</th>
<th>Building time</th>
<th>Maintenance costs</th>
<th>Demolishing costs</th>
<th>Lifespan</th>
<th>Presence of materials and equipment in Cuba</th>
<th>Logisic feasibility</th>
<th>TOTAL SCORE</th>
</tr>
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<tbody>
<tr>
<td>Zero ALT.</td>
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<td>1</td>
<td>5</td>
<td>1</td>
<td>3</td>
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<td>5</td>
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<td>Hard solutions</td>
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<td></td>
<td></td>
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<td>5</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>3.09</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>2.58</td>
</tr>
<tr>
<td>Soft solutions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>1</td>
<td>5</td>
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<td>4</td>
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<td>5</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>4.36</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>5</td>
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<td>2</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>3.61</td>
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<tr>
<td>3</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>5</td>
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<td>5</td>
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<td>5</td>
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<td>3</td>
<td>4.07</td>
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<td>4</td>
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<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>2.85</td>
</tr>
</tbody>
</table>

Table 9-6 Results of MCA
This results in the order of alternatives reflected in Table 9-7.

<table>
<thead>
<tr>
<th>Order</th>
<th>Hard Solution</th>
<th>Soft solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Offshore submerged breakwater</td>
<td>Nourishment on foreshore 20 - 37</td>
</tr>
<tr>
<td>2</td>
<td>Offshore emerged breakwater</td>
<td>Nourishment on foreshore and dunes of 20 - 37</td>
</tr>
<tr>
<td>3</td>
<td>Fishtailed breakwater</td>
<td>Nourishment on foreshore east of 20 - 37</td>
</tr>
<tr>
<td>4</td>
<td>Groins</td>
<td>Maintenance</td>
</tr>
<tr>
<td>5</td>
<td>Extension of Paso Malo breakwater</td>
<td></td>
</tr>
</tbody>
</table>

Table 9-7 Order of alternatives according to MCA

The zero alternative scores 3.14: Groins, Fishtailed breakwaters, Extension of the Paso Malo and Maintenance score lower clearly indicating that these solutions alone should never be applied to solve the erosion problems in the critical zone. A remark should be made by saying that in this MCA only single solutions are taken into account; maybe these solutions can form combinations with other solutions, scoring significant higher than the solutions on their own.
A sensitivity analysis of the MCA is made, to see if values change if other preferences are used. If other criteria's are made highly important, thus scoring only ones in the rows of Table 9-6. The results are shown in Table 9-8.

<table>
<thead>
<tr>
<th></th>
<th>Costs</th>
<th>Environment</th>
<th>Technique and Carrying out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero alternative</td>
<td>3.61</td>
<td>3.33</td>
<td>3.21</td>
</tr>
<tr>
<td><strong>Hard solutions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groins</td>
<td>3.11</td>
<td>2.84</td>
<td>3.32</td>
</tr>
<tr>
<td>Offshore emerged breakwater</td>
<td>3.58</td>
<td>3.54</td>
<td>3.96</td>
</tr>
<tr>
<td>Offshore submerged breakwater</td>
<td>3.75</td>
<td>3.87</td>
<td>4.12</td>
</tr>
<tr>
<td>Fishtailed breakwater</td>
<td>2.88</td>
<td>2.81</td>
<td>3.48</td>
</tr>
<tr>
<td>Extension of Paso Malo breakwater</td>
<td>2.58</td>
<td>2.56</td>
<td>2.92</td>
</tr>
<tr>
<td><strong>Soft solutions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nourishment on the foreshore of Calle 20 – 37</td>
<td>4.37</td>
<td>4.31</td>
<td>4.19</td>
</tr>
<tr>
<td>Nourishment on the foreshore east of Calle 20-37</td>
<td>3.82</td>
<td>3.64</td>
<td>3.64</td>
</tr>
<tr>
<td>Nourishment on the foreshore and dunes of Calle 20 -37</td>
<td>4.03</td>
<td>3.99</td>
<td>4.01</td>
</tr>
<tr>
<td>Nourishment on the foreshore of Calle 20 – 37</td>
<td>3.21</td>
<td>3.00</td>
<td>2.78</td>
</tr>
</tbody>
</table>

**Table 9-8 Scores in MCA using other preferences**

It is clear that the order of scores does almost not change when other preferences are used in the Multicriteria Analysis. Still the submerged offshore breakwater scores best of the hard solutions, and nourishment on the foreshore of Calle 20-37 scores best of the soft solutions.

These solutions will be worked out further in this research.
9.6 Summary

In this chapter possible hard and soft solutions for the erosion problems in the critical zone were considered and a first rough design is made. This is done for the following solutions: Groin, offshore emerged breakwater, offshore submerged breakwater, fishtailed breakwater, extension of Paso Malo breakwater, nourishment and maintenance. Different places of nourishment are considered.

Also a few non-engineering measures are considered that can contribute to solve the problems in the critical zone. These measures are not taken in account in the multi criteria analysis.

This analysis pointed out that a submerged offshore breakwater is the best hard solution, and nourishment on the foreshore and beach of Calle 20 – 37 is the best soft solution. Also when priority is given to another criterion, the analysis still indicates these two alternatives as best.
10 Nourishment

In chapter 9, nourishment on the foreshore and on the beach of Calle 23 – 37 was indicated as the best soft solution for the erosion problems in the critical zones. In this chapter a further design of this alternative is made.

First, the borrowing zone is determined and the location of the nourishment is described. After that, the amount that is needed for the nourishment is estimated with the use of guidelines and UNIBEST and the way of construction is described.

At the end of the chapter a measurement program that should be executed after the nourishment is described and the time schedule of the project is given, as well as a cost estimation.

10.1 Borrowing zone

The sand used for nourishment will be borrowed from the extraction zone used in previous nourishing programs on the peninsula, just south of Cayo Mono, about 10 kilometers from the critical zone. Estimations by CISMA indicate a total amount of sand of 5,000,000 m$^3$ that can be extracted from this site. The mean sand diameter of the extraction zone is 0.38mm, but different diameters can be found as reflected in figure 10-1.
Granulometry of the borrow area Cuenca de Mono before and after the Hurricane Michele

Figure 10-1 Sand diameters in the borrow zone (source: Institute of Oceanology)

Although the diameters measured in November and March 2001 show some differences, there is assumed that the diameters have not changed since November 2001.

The sand will be extracted from the borrowing zone with the use of a trailing suction hopper dredger.
10.2 Location of nourishment

The sand that is extracted from the borrow zone is nourished on the whole critical zone, from Calle 20 to 37.

The sand is nourished on the beach but also on the foreshore. This is done because when only the beach would be nourished, a large amount of sand should be added to the beach and the profile seaward would get very steep. This is not advisable for recreational activities; the present profile should not get very steeper. The present mean profile of the critical zone (profile number 3) is given in appendix 2.

When no measures are taken to improve the mean diameter, the sand used for nourishment has a mean sand diameter of 0.38mm. The width of the active profile in the critical zone is 990m and the depth 11.2 m.

10.3 Volume of sand to be nourished to compensate longshore transport

In this Paragraph, the amount of sand that needs to be nourished to compensate longshore transport is determined. First, the amount of sand is estimated by the use of guidelines. After that, that amount is checked in the UNIBEST model of the peninsula. Finally, the amount is determined. Only longshore transport of sediment is considered in this Paragraph; cross-shore transport is considered further on in this chapter.

10.3.1 Amount of nourished sand with guidelines

In this Paragraph, the amount of sand that should be nourished is estimated with the help of guidelines. This is done for the initial nourishment that should extend the beach width with at least 15 meters. But also for the nourishment program in the future that should prevent the coastline to retract further than 15 meters seaward of its current position. The return period of the maintenance nourishment is taken to be 5 years because this is the return period of the nourishments done until now at the Peninsula.
10.3.1.1 Initial nourishment

The purpose of the initial nourishment is to extend the beach at least 15 meters seaward for the next 5 years. The sand will be nourished mostly on the shore close to the beach and on the beach itself, creating a quick increase of the beach area. This causes a sudden change in the local morphological system; the nourishment will start eroding over a certain length, while the coastal compartment next to it will start accreting over the same length. In this Paragraph an estimation of the amount that erodes is made using the single-line theory.

No gradients in longshore transport are taken in account and square nourishment is assumed in order to make use of the guidelines. The relations are reflected in figure 10-3

![Graph](image)

**Figure 10-2 Optimal dimensions of nourishment**

With:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>l,b,a</td>
<td>Length, width and area of the desired coastal extension</td>
</tr>
<tr>
<td>L,B,A</td>
<td>Length, width and area of nourishment on t = 0</td>
</tr>
<tr>
<td>x₀</td>
<td>((L-l)/2)</td>
</tr>
<tr>
<td>L₀</td>
<td>(4(s/h)t)</td>
</tr>
<tr>
<td>s</td>
<td>Variation of the longshore transport as a function of the angle rotation of the coast line.</td>
</tr>
<tr>
<td>h</td>
<td>Height of the active coast profile</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
</tr>
</tbody>
</table>
In order to calculate the amount, the variation of the longshore transport as a function of the angle rotation of the coast line ($s$) is needed. This variation is obtained from UNIBEST. See appendix 19, figure 1. The figure indicates an $s$ of 143.000m$^3$/rad/year.

In the calculation, the sea level rise can be taken in account: the regression of the coastline due to sea level rise has to be added to the 15 meters of beach extension. This leads to a value of 15.7 meters.

So, in five years the coast line should be extended 15.66 meters seaward and the length of it should be 1500 meters. Figure 10-3 then indicates initial nourishment with a length of 2300 m and a width of 17.2 m.

With the beach profile, these numbers can be translated into an amount of sand that needs to be nourished. Assuming it is a straight profile from (0,0) to (990,-11.2) that moves 17.2 meters seaward. If a larger grain size is used the profile gets steeper. This process can be illustrated with the following equation:

$$I_2 = (w_1 / w_2)^{0.56} \cdot I_1$$  \hspace{1cm} (Formula 10.1)

In which:
- $I_2$ New distance of depth line to water line
- $I_1$ Old distance of depth line to water line
- $w_1$ Fall velocity of the original sand
- $w_2$ Fall velocity of the new sand

The fall velocities can be obtained from the graph in appendix 4. This leads to an $I_2$ that is 0.85 x $I_1$. So, if the coast line moves 17.2m on the surface, at the end of the dynamic zone, on the bottom, the profile only moves 14.6 m seaward. With these numbers the amount of sand that needs to be nourished can be determined. It is the volume between the old and the new profile. With the values of $I_1$ and $I_2$ a new beach slope of 1.13% can be calculated.

A total amount of 178m$^3$ of sand must be nourished per meter. The total amount that should be nourished then is 178 x 2300 = 409,400m$^3$.

This amount needs to be compensated for the different characteristics of the sand used in the nourishment in comparison with the native sand. This can be done with
two models given in the Shore Protection Manual. The first one is the 'adjusted SPM fill factor' \( R_a \), indicating the under- or overdimension of the sand. The second one is the 'renourishment factor \( R_r \)' indicating a longer or shorter time that renourishment is needed.

**Adjusted SPM fill factor**

The adjusted SPM fill factor can be determined from figure 2 in Appendix 19. In this figure, the sand characteristics are represented by \( \Phi \).

\[
\Phi = -^{2}\log{D}
\]  
(Formula 10.2)

With:

\( D \) = grain size in mm.

Furthermore,

\[
M\Phi = (\Phi_{84} + \Phi_{50} + \Phi_{16})/3
\]

\( \sigma\Phi = (\Phi_{84} - \Phi_{16})/2 \)

(Formula 10.3)

(Formula 10.4)

with:

\( M\Phi \)  The mean value of \( \Phi \)

\( \sigma\Phi \)  The standard deviation of \( \Phi \)

\( n \)  Native

\( b \)  Borrowed.

The native sand characteristics can be determined from the measurements done near Calle 23. The borrowed sand characteristics are displayed in table 1 of appendix 19.

This leads to the values displayed in table 10-1.

<table>
<thead>
<tr>
<th></th>
<th>Native Sand</th>
<th>Borrowed Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M\Phi )</td>
<td>1.69</td>
<td>1.51</td>
</tr>
<tr>
<td>( \sigma\Phi )</td>
<td>0.78</td>
<td>0.93</td>
</tr>
<tr>
<td>( M\Phi_n-M\Phi_b/\sigma\Phi_n )</td>
<td>-0.2</td>
<td></td>
</tr>
<tr>
<td>( \sigma\Phi_n/\sigma\Phi_n )</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

**Table 10-1 Characteristics of native and borrowed sand**

---

\(^1\) James, 1975
From figure 2 in appendix 19 there can be determined that the adjusted SPM fill factor is 1.02. This indicates that to compensate the washing away of small particles during the nourishment, 2% extra sand needs to be nourished. This leads to a total amount of about 417.600m³.

Renourishment factor
The renourishment factor can be determined from figure 3 in appendix 19. With the use of the values in table 10-1, a renourishment factor of 0.66 is found. This indicates that the time renourishment is needed is enlarged with \((1/0.66 - 1) \times 100\% = 52\%\) in comparison with a nourishment with the same sand as the native.

This effect of the use of a bigger mean grain size on the renourishment time will occur every nourishment, as in general always a little bigger grain size should be nourished to the beach. However, it is not possible to determine the grain sizes that will be used in the future nourishments right now; therefore, the size of the effect in the future is uncertain.

10.3.1.2 Maintenance nourishment

To maintain the extra beach width of 15 meters, every five year the beach will be nourished. The amount that needs to be nourished can be easily estimated with use of the single-line theory from figure 10-3. As in five years the white amount of sand has disappeared, a nourishment of the same amount will prevent the dashed area to erode in the next five years. See figure 10-3.

![Figure 10-3 Eroded amount](image)

Assuming that the whole profile will move backwards due to erosion, the amount of sand that is eroded after five years is 179.400m³. This is the amount of sand that
should be nourished every five years to compensate the loss of sand due to longshore transport.

The total amount of sand that is nourished in 50 years is reflected in table 10-2.

<table>
<thead>
<tr>
<th>Amounts in m³</th>
<th>Number of times</th>
<th>Amount per time (m³)</th>
<th>Amount per Nourishment (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Nourishment</td>
<td>1</td>
<td>417.600</td>
<td>417.600</td>
</tr>
<tr>
<td>Maintenance Nourishment</td>
<td>9</td>
<td>179.400</td>
<td>1.614.600</td>
</tr>
<tr>
<td>Total needed in 50 yr:</td>
<td></td>
<td></td>
<td>2.032.200</td>
</tr>
</tbody>
</table>

Table 10-2 Total amount of sand needed in 50 years

10.3.1.3 Conclusion

To achieve a dry beach zone width of 15 meters more (than presently) between Calle 20 and 37, an amount of 417.600 m³ has to be placed between over a total length of 2300 meter. To keep this stretch of dry beach, an amount of 179.400 m³ is needed every 5 years.

The total amount of sand needed in 50 years is: 2.032.200 m³.

10.3.2 Amount of nourished sand with UNIBEST

The beach has to be extended with 15 meter as is demanded. With the method described below the amount needed to create the extension of 15 m and the amount needed to keep this stretch of dry beach was determined.

In UNIBEST one can define sources to simulate an input of sediment (such as rivers and beach nourishments). To simulate beach nourishment at Calle 20 to Calle 37 there are 3 sources of sediment appointed to the coast (there are 3 [calculation] points at this stretch of coast). The 3 sources coincide with the Calles 23, 30 and 37. The critical zone is from Calle 20 to 37 so, to check whether the beach nourishment is sufficient, the change of coastline is monitored at Calle 20, 23 and 37. Two notes have to be made here:

- The 'nourished' sand has the same diameter as the original beach. In reality this will not be the case.
The amounts needed to get the demanded result (15 m extra dry beach and fixation of that coastline) are found by trial and error. First the amount needed for a beach extension of 15 m is determined by trying a volume (different for each of the 3 points) so that after 5 years the coastline along the whole critical zone increases approximately 15 m. Then (based on the volume lost in 50 years without maintenance) a first estimation of the amount needed to keep the coastline fixed is made. This amount is taken as the amount that should be placed on the beach every 5 year to prevent a regression of the coastline past the 15 m wanted. With another trial and error cycle the final amount needed every 5 years was determined.

10.3.2.1 Initial nourishment

To increase the original coastline with 15 meter a large amount has to be nourished first.

For each of the three locations where sand is nourished, the following values (table 10-3) were found to get an initial increase of the coastline with 15 m along the stretch of Calle 20 to 37.

<table>
<thead>
<tr>
<th>Initial nourishment</th>
<th>Calle 23</th>
<th>Calle 30</th>
<th>Calle 37</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount (m³)</td>
<td>170,000</td>
<td>157,500</td>
<td>127,500</td>
</tr>
</tbody>
</table>

Table 10-3: Amounts needed per source for increase of dry beach zone

The total amount needed for the increase of the coastline with 15m width is therefore 455,000 m³.

10.3.2.2 Maintenance nourishment

To keep the initial increase of 15 m of the dry beach zone (fixed at least) a maintenance program has to be developed. Every 5 years after the initial nourishment maintenance nourishment will have to be done. The amounts needed for these maintenances are given for the three locations where sediment is placed:

---

Project group CF015 222
Table 10-4: Amounts needed per source every 5 years for fixation of the 15 meter dry beach zone

<table>
<thead>
<tr>
<th>Maintenance nourishment</th>
<th>Calle 23</th>
<th>Calle 30</th>
<th>Calle 37</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount (m³)</td>
<td>42.000</td>
<td>50.000</td>
<td>12.000</td>
</tr>
</tbody>
</table>

The total volume needed every 5 years is therefore: 104.000 m³.

**Coastline at critical zone**

If the described nourishments are applied the coastline will change in 50 years according to the graph below (figure 10-5):

![Change of coastline with initial nourishment and maintenance](image)

**Figure 10-4 Change of coastline**

It can be seen that the coastline after 30 years is very close to the 15 m extension of the beach. After that period however the coastline increases due to changes in the local coastal angle. And after another 20 years (50 years in the graph) the coastline has increased even more. This means that after 30 years a smaller amount can be placed near Calle 23. The measures described above will extend the beach width with 15 m and keep the coastline.
The total amount needed in 50 years is reflected in Table 10-5.

<table>
<thead>
<tr>
<th>Amounts in m$^3$</th>
<th>Number of times</th>
<th>Amount per time (m$^3$)</th>
<th>Amount per Nourishment (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Nourishment</td>
<td>1</td>
<td>455.000</td>
<td>455.000</td>
</tr>
<tr>
<td>Maintenance Nourishment</td>
<td>9</td>
<td>104.000</td>
<td>936.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total needed in 50 yr: 1.391.000</td>
</tr>
</tbody>
</table>

Table 10-5 Total amount of sand needed in 50 years – UNIBEST

10.3.2.3 Conclusion

To achieve a dry beach zone width of 15 m more (then presently) between Calle 20 and 37, an amount of 455.000 m$^3$ has to be placed between Calle 23 and 37. To keep the coastline from retracting towards the coast an amount of 104.000 m$^3$ is needed every 5 years.

The total amount of sand needed in 50 years is: 1.391.000 m$^3$.

10.3.3 Evaluation

The initial amount that should be nourished to the critical zone is 455.000 m$^3$ according to the guidelines, and 417.600 m$^3$ according to the UNIBEST model. This could be explained by the fact that UNIBEST does not take into account the change of the sand characteristics but also by the fact that the guidelines are a further simplification of reality than UNIBEST. Furthermore in the estimation with guidelines, sea level rise is included; in UNIBEST, it is not.

To ensure the success of the nourishment, the amount of the initial nourishment can best be chosen conservative. As both values do not differ very much, it is better to take the higher value.

The amount of nourished sand for maintenance differs a lot more between both estimations. Where the estimation by the use of guidelines indicated 179.400 m$^3$, the UNIBEST model indicated only 104.000 m$^3$. The estimation by the use of guidelines shows a more conservative result. This could be explained by the facts that in the
estimation with the guidelines sea level rise and the adjusted SPM spill factor is included, and that the calculations were very sensitive for these parameters.

In both calculations, the longer renourishment time caused by the use of larger grain sizes is not taken in account. This longer renourishment time indicates that the amount of sand that should be nourished is less than calculated.

Again, the amount of sand that should be nourished should be chosen conservative, but based on the data from UNIBEST as the estimations by the guidelines are considered too rough. The UNIBEST data however should be compensated for sea level rise and the adjusted SPM spill factor.

No renourishment factor is taken into account here, which probably leads to an overdimension. Not taking in account this factor can be seen as taking in account a safety factor.

10.3.4 Conclusion

The total amount of the initial nourishment is 455.000. When the effects of sea level rise and the adjusted SPM spill factor are used on the UNIBEST data, it leads to a maintenance nourishment indicated on 125.000m³ every five years, but as estimations between the two used methods differ significantly this amount should be reconsidered after five years when sufficient measurements should be available.

After the nourishment, a new beach slope of 1.13% is created.
10.4 Amount of sand to be nourished to compensate cross-shore transport

In chapter 7, it is indicated that severe storms can influence the amount of sand present on the beach significantly, as Hurricane Michelle eroded almost 40.000 m$^3$ of sand from the critical zone. Because the natural dune-beach system was interfered, this sand does not make its way back to the beach and accumulates in banks on the foreshore. No sand is lost in the cross-shore section, but in this way the dry beach width is of course decreased.

Hurricanes and storms influencing the Peninsula de Hicacos are not rare phenomena. Therefore the amount of sand eroded by these phenomena should be taken into account in the nourishment program. In this Paragraph, an estimation of the amount of sand that should be nourished to compensate cross-shore erosion is made.

10.4.1 Initial nourishment

After the original nourishment, the beach width is increased with 16.5 meters, and the effects of the dune-beach disturbance are decreased as winds can blow back sand again. Erosion will occur after storms, the long-time effects of this however will be less as the beach recuperates more.

The calculations made in chapter 7 have their limitations, as concluded. However, not enough measurements have been carried out to determine the amount of cross-shore transport during storms. Therefore, for the initial nourishment the amount that needs to be nourished will be based on the calculations made in chapter 7.

An amount of approximately 38.000 m$^3$ of sand was eroded during Hurricane Michelle. For the Peninsula de Hicacos, Hurricane Michelle was the severest Hurricane of the last decades, and it can be concluded that normally during other hurricanes and storms less sand will be eroded. If we extend the trend indicated in figure 4-12, about two storms per year can be expected, resulting in a total of 10 storms per 5 year. The effects of the storms will become less with their occurrence, as the beach already is adapted to the new circumstances, and bar formations already are formed. For now, the circumstances of Michelle will be considered normative. This means that the maximum size of the bar formation is assumed to be 40.000 m$^3$. Therefore, this
should be the amount of sand that should be nourished to compensate losses due to cross-shore transport.

These assumptions need verification by measurements of the bar formations after the nourishment. If these are estimated too low, sand will have to be brought back to the beach from the banks artificially to ensure a beach width of 15 meters seawards to its current position.

With this assumption, an extra amount of about 40,000 m$^3$ of sand needs to be nourished in the initial nourishment.

### 10.4.2 Maintenance nourishment

The amount of sand that should be nourished in the maintenance nourishments to compensate cross-shore erosion in the future is very difficult to estimate. This amount should be obtained from measurements in the measurement program after the nourishment. It is sensitive to the occurrence and force of the storms in the future as well as to the dune-beach system in the future.

However, to make cost estimation, it is now assumed that 40,000 m$^3$ of sand needs to be nourished every five years. This assumption is based on Hurricane Michelle, see Paragraph 7.3.2.

### 10.4.3 Evaluation

The amount of sand that is lost from the beach in cross-shore direction is difficult to estimate, as was already concluded in chapter 7. However, because no sufficient measurements are available, for the initial nourishment the losses have to be estimated. The estimation is very rough, based solely on one hurricane (Michelle), as no other data is available.

In order to make a good estimation for the maintenance nourishment, but also to check the assumptions made for the initial nourishment, data should be obtained from the measurement program after the nourishment.
10.4.4 Conclusion

The amount of sand that should be nourished extra in the initial nourishment in order to compensate cross-shore transport is estimated on 40.000m³. This estimation is based on Hurricane Michelle.

To check this estimation and to make an estimation of the amount of sand that should be nourished extra in the maintenance nourishments a good measurement program should be executed. To make cost estimation, an amount of 40.000m³ of sand per maintenance nourishment is assumed.
10.5 Total amount

The total amount of sand that should be nourished in the initial nourishment is 495.000 m³; 455.000 m³ of that is used to compensate losses due to longshore transport and global sea level rise. The other 40.000 m³ is to compensate cross-shore transport.

The amount that is nourished in the maintenance nourishment is estimated to be 165.000 m³; 125.000 m³ to compensate longshore transport and sea level rise, and about 40.000 m³ to compensate cross-shore transport.

10.6 Execution

The sand is extracted from the borrowing zone near Cayo Mono by a trailing suction hopper dredger, present in the current Cuban dredging fleet. This sand does not have to be improved, so no measurements have to be taken during the extraction. The trailing suction hopper dredger transports the sand close to the coast, and with the help of a floating booster (also present in the Cuban dredging fleet) via a pipeline it is transported further to a booming pontoon. This is done because the shallow water near to the coast does not allow the trailing suction hopper dredger to come closer.

From this pontoon, the sand/water mixture is boomed on the beach and foreshore. With the use of the floating booster distances up to approximately 50 to 60 meter can be bridged. However, the net distance of course will be less, because the sand/water mixture will partly stream back. On the beach, the sand is spread out with the use of bulldozers, creating a flat beach.

Where the water depth allows this, the trailing suction hopper dredger dumps the sand via its bottom. When water depth gets less, certain distance can be bridged by booming from the dredger. When depth gets lesser and booming from the dredger is no longer an option, the booming pontoon is used (Figure 10-5).

After the nourishment, there should be considered if it is necessary to artificially restore vegetation on the dunes in the critical zone, if there is damage done to it.
10.7 Measurement program

Because there is no Cuban regulation known on measurement programs, the measurement program is based on Dutch principles.

Profile measurements should be done during the nourishment to monitor the progress and to determine the amount of sand that is nourished. Every week, the nourished part needs to be measured, at distances of 50m. At the end of the nourishment, the whole area should be measured; this measurement is the final of the nourishment.

To check the effect of the nourishment, but also to obtain new data on for example cross-shore transport, also an extensive measurement program needs to be executed after the nourishment.

In comparison with the profile measurements that have been executed in the past by the Institute of Oceanology, it is very important that the measurements have the same vertical reference level. Also, measurements should be done up to the border of the dynamic zone, 990m out of the coast. Otherwise, not all the sediment transport is taken in account in the measurements, as clearly indicated by the output of UNIBEST.

Profile measurements should be done every three months after the nourishment during the whole renourishment period of five years. Also, measurements should be
done after severe storms, as they indicate the amount of sand that is transported cross-shore. The distance between the profile measurements should be about 200m. The profile measurements should give insight in the morphological behavior of the nourishment but also important information on the cross-shore transport due to storms.

Before the nourishment, right after and from then every year also sand samples should be taken. These samples should be mainly examined on their grain size. These measurements are done to indicate the sediment transport (grain size changes) within the nourished area, but also of the total area.

10.8 Time schedule

Based on the former nourishment in 1998, an indication can be given about the time needed for the nourishment. As in 1998 about 1,000,000 m³ of sand was nourished in nine weeks, a nourishment of about 500,000 m³ should take 5 weeks. The best time to nourish is in the months July and August, as tourist activity is lower and the weather is usually calm. Measurements of the profile should take place every three months beginning right after the nourishment. Also, after significant storms the profile needs to be measured. Every year, sand samples should be taken.

The time needed for the maintenance nourishments will be about 2 weeks, as only 165,000 m³ is nourished.

10.9 Cost estimation

With the use of Cuban sources on cost estimation, estimation is made of the total costs of the nourishment program. First, the costs of the initial nourishment are estimated. After that, the costs of the maintenance nourishment are estimated. Finally, the total costs of the nourishment program are calculated.

As the costs of the maintenance nourishment are made in the future, for comparison they have to be translated in current costs. The discount rate is based on Dutch standards and estimated on 5%.

The total costs of the maintenance nourishment are translated in present day costs in table 10.8. From these values, the total cost of the nourishment is estimated.
<table>
<thead>
<tr>
<th>Year</th>
<th>Action</th>
<th>Costs at that year</th>
<th>Factor</th>
<th>Cost at year 0</th>
</tr>
</thead>
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<tr>
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<td>Initial nourishment</td>
<td>$777.309</td>
<td>1.00</td>
<td>$777.309</td>
</tr>
<tr>
<td>5</td>
<td>Maintenance 1</td>
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<td>0.78</td>
<td>$258.526</td>
</tr>
<tr>
<td>10</td>
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<td>$331.443</td>
<td>0.61</td>
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<td>$125.948</td>
</tr>
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</tr>
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<tr>
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</tr>
<tr>
<td>45</td>
<td>Maintenance 9</td>
<td>$331.443</td>
<td>0.11</td>
<td>$36.459</td>
</tr>
<tr>
<td></td>
<td>TOTAL COST</td>
<td></td>
<td></td>
<td>$1.837.924</td>
</tr>
</tbody>
</table>

Table 10-6 Total costs of nourishment

So, the total cost of the nourishment program for 50 years is 1.837.924 U.S.dollars.

This amount is based on the assumption that only Cuban equipment would be used. If Cuban equipment is not available, awarding the contract to an international dredging contractor would increase the cost of nourishing. Mobilisation and installation costs would be charged as well as demobilisation. Nevertheless these costs are not fixed. The contractor may choose to vary them according to his business strategy.

The calculations of the costs are presented in Appendix 20 and 21.
10.10 Summary

The sand for the nourishment will be extracted from the borrow zone that was also used in former nourishments, just south of Cayo Mono and approximately 10 km from the critical zone. The mean diameter of this sand is 0.38 mm.

The sand will be nourished on the foreshore and on the beach of the critical zone. In the initial nourishment 465,000 m$^3$ of sand is nourished, in the maintenance nourishments every five years 165,000 m$^3$ is nourished. This ensures a minimum beach width of 15 meters seawards of its current position.

The sand will be extracted with the use of a trailing suction hopper dredger, and nourished on the beach and shallow water by booming. Booming is done from a booming pontoon, connected to a floating booster that is connected to the dredger. In deeper water, the sand can be dumped by the dredger.

Profile measurements with a fixed reference point should be executed before, during and after the nourishment. During the nourishment this should be done every week, after the nourishment every three months and after significant storms. Also, every year sand samples should be taken.

The time needed for the initial nourishment is about 5 weeks, and for the maintenance nourishment it is about 2 weeks. Maintenance nourishment is executed every five years.

The cost of the initial nourishment is estimated at $777,309. The cost of the maintenance nourishment is estimated at $331,443. Taking into account a discount rate of 5%, this leads to a total cost of about $1,800,000 for the nourishment program (present day value).
11 Offshore submerged breakwater

11.1 Introduction

The main objective of this chapter is the hard type solution of the erosion problem. The hard type solution consists of the construction of a breakwater. If still some erosion is detected a breakwater could be combined with beach nourishment. A breakwater is used to change the wave climate near the beach. Before one is able to design a breakwater the desired wave climate should be known. This calculation is done in UNIBEST, which uses the ENDEC\textsuperscript{1} wave model. The first calculation will be used to get an impression which waves cause the most erosion. After this determination the location of the breakwater will be fixed. When the location and the desired wave climate behind the breakwater are known the dimensions and the stability of the breakwater will be determined. Finally the construction and the costs of the breakwater are described in one of the last Paragraphs of this chapter.

11.2 Design of a breakwater using the UNIBEST model

11.2.1 Location of the breakwater

To determine the location of the breakwater it is necessary to know which waves have to be reduced.

With the help of the UNIBEST peninsula model, the amount of sediment transported in the zone for every significant wave at deep water is computed. In other words: The amount of sediment transported per significant wave (figure 11.1).

\textsuperscript{1} (Prof.dr.ir. Battjes and Prof.dr.ir. Stive, TU Delft 1974)
This figure shows that the waves at deep water with significant heights; 1.5 m, 2.5 m and 3.5m cause the most sediment transport. So in order to let these waves of 3.5 m break on the breakwater, the breakwater has to be located just in front of the place where these waves break themselves. If the breakwater is placed further offshore, the costs will increase because a larger amount of material is needed due to the fact that water depth increases and the breakwater has to be stronger to withstand the energy of higher waves that will break on the slope. In other words the breakwater should be resistant for higher waves, which requires a different composition of the breakwater.

To determine the water depth at which the waves break, the UNIBEST model shows that the 2.5m and 3.5 meter waves break at a distance of approximately 500m from the shore (see figure 11-2).
So the location of the breakwater is 500m from the shore. This also makes sense because at 500m from the shore the second sand bar begins.

11.2.2 Wave climate for UNIBEST

The UNIBEST model calculates wave heights at a distance 500m from the shore with the use of the ENDEC wave model. To determine these heights the values are read from the graphs presented in UNIBEST. These values are presented in figure 11-3. This should be taken into account for the determination of the dimension of the breakwater.

The deep water wave heights of 8.5m and higher are neglected because their occurrence is very small.
Figure 11-3 Wave heights in front of the breakwater

To calculate the wave climate between the breakwater and the shore the following assumptions are made:

- Breakwater is located at a distance of 500m from the shore
- Depth at 500m is 4.3 m.
- Crest height is assumed 1.5m below MSL (According to the list of demands).
- Wave height and angles of the incident waves are calculated by UNIBEST, based on the ENDEC model.
- No diffraction is taken into account, because the assumption is made that this phenomenon has only small influence on the wave height behind the breakwater, due to the width of the breakwater and its small distance from the shore.
- Only one uniform wave climate is taken into account between the breakwater and the shore.
- Transmitted waves are calculated in Cress using the Van der Meer equation for transmission of waves over a submerged breakwater.
- For waves which break on the breakwater; transmitted wave angle equals the breaking wave angle calculated with Cress.
- For waves which do not break at the breakwater; transmitted wave angle does not change, so the transmitted wave angle equals incident wave angle.

The Van der Meer equation for transmitted waves uses a linear equation, depending only on the incident wave height and the crest height under the sea level.
UNIBEST assumes that the breakwater is at the dynamic border: this means that only the sediment transport capacity in the area between coast and breakwater is taken into account. In this case, however, it has to be placed more close to the coast \((X_1 = 500 \text{ m})\) to avoid enormous breakwater dimensions because of the large depth of the sea at the dynamic border (which is 11 m at \(X_2 = 1000 \text{ m from the coast}\)).

UNIBEST calculates the amount of erosion or accretion by comparing the sediment transport capacities in both zones. Therefore, the sediment transport between breakwater and dynamic zone \((Q_{s1})\) has to be estimated and accounted for. This transport capacity will approximately be the same just east of the breakwater \((Q_{s2}, \text{ from } 500 \text{ m out of the coast till the dynamic border at } 1000 \text{ m } = X_2-X_1)\). This transport capacity was determined with the by-pass function (which gives the distribution of the transport capacity from a distance of the dynamic border, which is therefore 100% at the coastline) and it was found to be 45,600 m³ per year. This amount is 40% of the total transport in dynamic zone just east of the breakwater \((Q_{tot})\) which is 114,100 m³/year.

To compensate for this lack in the transport capacity behind the breakwater, 45,600 m³ per year will be removed from the eastern boundary (using a ‘sink’ of sediment) and replaced at the western boundary (using a ‘source’ of sediment). This way the sediment transport on the seaward side of the breakwater is accounted for.
Figure 11-5 Sediment transport between breakwater and the coast

The total transport between the breakwater and the coast is 31.200m³ (= Qs₃) (see figure 11-5).
Just east of the breakwater in the same cross shore section a transport capacity (Qs₄) of 68.500 m³ per year was found (60 % of the 114.100 m³) which means that the breakwater reduced this part of the transport capacity with about a half (Qs₄ - Qs₃).

11.3 Breakwaters modeled in UNIBEST

The input to simulate the wave climate behind the breakwater is given in Appendix 22.
To get a better picture of where the location of the breakwaters is, an overview is given below (Figure 11-6):
Figure 11-6: Location of Calle 20 to Calle 37 on the Peninsula

All other pictures in the next part of the Paragraph concern the critical zone only. Some points will be used at the critical zone for orientation and determination of calculation points. These points are the Calles, the streets perpendicular to the coast. The following Calles are important in the rest of this part where output is given: Calle 20, 23, 30 and 37. Their place along the critical zone is shown below:

Figure 11-7: The critical zone of Calle 20 to Calle 37

The total length of the critical zone is 1200 m and there are 7 points (seen as the green dots in figure 11-7) where output can be given from UNIBEST for erosion or accretion rates and sediment transport capacities.
11.3.1.1 UNIBEST results for small breakwater

First a small breakwater of 200m at a distance of 500m of the coast will be described. This breakwater will change the wave climate behind it, and therefore also the transport capacity. That is why the location of the breakwater is important. The mean direction of the wave climate is from almost north due to the large occurrence of waves from north and northeast in comparison with the waves from west and northwest.

To have the largest impact on the waves, which would reach the critical area, the breakwater is placed in front of Calle 37, the eastern boundary of the critical area.

The local wave climate behind it was already determined. The influence of the breakwater on the sediment transport is determined and then the amount of nourishment needed is determined to get an increase of the coastline with 15m and keep that width for the following 50 years. The location of the breakwater is therefore (figure 11-8):

![Diagram of small breakwater location and size](image)

*Figure 11-8 Location and size of the small breakwater*

Change of coastline

If the small breakwater is placed 500 m in front of Calle 37 and no other measures (like nourishment) are taken, the change of coastline in 5 years will be as presented in figure 11-9 (after 5 years the coastline gets instable due to the large change of the coastal angle):
Nourishment program
In order to get an increase of 15 m dry beach and to keep that distance for 50 years a nourishment program was determined through trial and error (if accretion occurred in one place less sand is placed there and the other way around). Below (figure 11-10) the change of coastline is given in case of a small breakwater during 50 years with the nourishment program applied that was found to fit the demands best.
The demand of 15 meters extra coastline is reached almost everywhere along the critical zone the first 10 years, and certainly after 10 years. This means that a little more sand is needed the first 30 years near Calle 37.

To the east of Calle 37 the coastline doesn’t change in the 50 years more significantly than without the breakwater and nourishment. To the west of Calle 20 however, more sediment arrives because of the nourishment and maintenance. This can be explained by the effect that without nourishment and maintenance there would be erosion at this spot actually. This extra sediment causes more accretion from the Paso Malo mouth towards the east. The influence of the accretion even reaches (after 40 years) to Calle 20 and causes the coastline there to increase on an even larger rate (as can be seen in the graph above).

**Amount of nourishment and maintenance**
The initial nourishment needed to get an increase along the entire stretch of 15m dry beach is 404,500m$^3$ for the total area of 1200m.

In order to keep at least this increase, an amount has to be placed every 5 year of 112,600m$^3$.

Two remarks are made here:

- More dry beach is achieved than demanded in some places (near Calle 20, 23) after 50 years, this is because the accretion east of the breakwaters of the Paso Malo has some influence on the coastal angle west of Calle 20. In reality some sand is removed from the east side of the Paso Malo to place it elsewhere on the Peninsula.

- Some sediment was removed west of Calle 37 each year in the model because of the accretion there. This can be used to place near Calle 30 where there occurs some erosion due to the influence of the breakwater on the local wave climate. The value of 112,600m$^3$ is therefore the amount of sediment needed from outside the critical zone. An amount of 66,900m$^3$ has to be replaced every 5 year within the critical zone (from Calle 34 to Calle 30).

**11.3.1.2 UNIBEST results for large breakwater**

One large breakwater is placed in front of almost the entire stretch of Calle 20 to Calle 37, 500m out of the coast (figure 11-11).
If the large breakwater is placed 500m out of the coast, the change of coastline during 5 year will be as presented in figure 11-12. (After 5 years the coastline in the model gets instable due to the large local differences in coastal angle)

**Figure 11-12 Coastal change due to large breakwater (5yrs)**

*Nourishment program*

In order to get an increase of 15m dry beach and to keep it for 50 years a nourishment program was determined through trial and error again. Below (figure 11-13) the change of coastline is given in case of a large breakwater during 50 years with the nourishment program applied that was found to fit the demands best.
Along the entire stretch there is an increase of 15 meters immediately after the initial nourishment (at t=0 years).

The initial nourishment needed to extend the dry beach with 15 m consists of 173,100 m$^3$ spread over the entire 1200m of the critical zone. The amount that has to be placed on the stretch every 5 years to keep the coastline more or less fixed is 46,000m$^3$.

Two remarks are made here:

- Sand was removed from Calle 37 every 5 years because there is a lot of accretion due to the mild wave climate caused by the breakwater. The sediment obtained from this eastern part can be used to place it in the western part near Calle 20 where sand is needed. An amount of 68,500 m$^3$ can be replaced within the zone from the eastern to the western parts every 5 years, so this amount doesn’t need to be brought to the critical zone from another place.

- After 30 years there is a larger increase near Calle 20 due to the influence of the accretion east of the Paso Malo breakwaters: after that a smaller amount of sand can be placed on the beaches to keep the 15 m extra dry beach (not taken into account here). To the east of Calle 37 the coastline doesn’t change in the 50 years more significantly than without the breakwater and nourishment. This is actually the same effect as observed with a breakwater of 200 m length.


11.4 Dimensions

11.4.1 Introduction
As mentioned in the bill of demands, the freeboard of the breakwater should not be less than one meter below the water surface. In this chapter the water depth above the breakwater is determined on 1.5m and the bottom level is fixed on 4.3 m below mean sea level. This means that the crest height of the breakwater is approximately 2.8 m.

In order the determine the other dimensions of the breakwater some parameters have to be determined first, e.g. nominal grain size diameter, type of material, number of layers, thickness of the layers, slope etc. These topics will appear in this paragraph. The composition of the breakwater is only roughly determined in this report, mainly because detailed design of the breakwater is not in comprised in the main objective of this project.

11.4.2 Determination of nominal grain size diameter
The top-layer of the breakwater determines the nominal grain size diameter ($D_{50}$). To make a design of the top layer, a few factors have to be taken in consideration:

- Material of armour layer
- Stability of the layer under extreme conditions
- Stability of the layer under normal conditions

11.4.2.1 Material of the armour layer
The armour layer has to protect the breakwater against the wave energy from the breaking waves. This layer can be made of different materials. The materials taken into account for the breakwater are:

- Quarry rock
- Concrete cubes
- Tetrapods

A rubble structure is composed of several layers of random-shaped and random-placed stones, protected with a cover layer of selected armour units of either quarry stone or specially shaped concrete units. Armour units in the cover layer may be placed in orderly manner to obtain good wedging or interlocking action between individual units, or they may be placed at random. Present technology does not
provide guidance to determine the forces required to displace individual armour units from the covering layer. Armour units may be placed over a large area of the cover layer, sliding down the slope en masse, or individual armour units may be lifted and rolled either up or down the slope. Empirical methods have been developed that will give a satisfactory determination of the stability characteristics of these structures when under attack by storm waves.

To ensure the stability of the breakwater, the minimum diameter or weight of the used stones has to be determined. The top-layer has to resist the wave energy and will therefore consist of the largest stones. To design an economic breakwater, the breakwater will be constructed in different layers, with different stone diameters. The under-layers and core still have to transmit the forces to the ground and prevent washing out of the layer under it.

In this case, the wave attack will be at the crest, because of the submergence character of the breakwater and the stability of the block depends largely on the weight of the blocks instead of interlocking. High placing criteria has to be applied when concrete units are used to increase the stability at the crest. This is especially the case with complicated units as Tetrapods. Cuba has experience in making Tetrapods as they have been used in the western part of Havana, but the complexity of the shuttering for their fabrication is high. The more complicated the units, the higher the costs. Concrete cubes are on the other hand easy to construct. A disadvantage is that the concrete is not used efficiently.

Costs are an important factor when making a choice which material will be used. The costs of the stones are strongly dependant on the transportation and production costs. Quarry rock has to be transported from the south of Cuba (about 700 to 800 km away) and the production is not standard, which has a negative effect on the costs. A concrete factory is present in Havana, which reduces the transportation costs for concrete units largely.

Taking into account the transportation and production costs the choice has been made that in the next phases of the project concrete cubes will be used.

11.4.2.2 Stability of the layer under extreme conditions

For the determination of the grain size diameter \( \left( D_{n50} \right) \) for the stability of the concrete cubes, an empirical Van der Meer formula (1990) and an equation for submerged breakwaters \( (R_c<0) \) can be applied. The equation is developed for the stability of irregularly shaped natural rock. The \( D_{n5C} \) is defined differently than for regularly shaped concrete cubes, but the average will be the same. Therefore, it will be assumed that the \( D_{n50} \) stability formulas for quarry rock can be applied to concrete cubes.
For submerged breakwaters, the stability is a function of the relative crest height $h_c/h$, the damage level $S$, and the spectral stability number $N_s$ (see formula 11.1). The given formulas are based on a specific analysis for the CUR/CIRIA (1991) by Van der Meer (1990) to re-analyze the tests of Givler and Sørensen (1986).

$$D_{n50} = \left[ -0.14 \cdot H_s \cdot s_p \cdot \frac{\gamma}{\Delta \cdot \ln \left( \frac{h_c}{h \cdot (2.1 + 0.1 \cdot S)} \right)} \right]$$  

Formula 11.1

In which:

$H_s$  Significant wave height (m)

$s_p$  Local wave steepness: $\frac{H}{L}$ (\cdot)

$\Delta$  Relative density: $\frac{\rho_1 - \rho_2}{\rho}$ (\cdot)

$h_c$  Crest height of the breakwater (m)

$h$  Water depth (m)

$S$  Damage level (\cdot)

The extreme wave conditions are determined in bill of demands. For the location of the breakwater at a distance of 500m from the shore, the ENDEC model in UNIBEST calculated that the highest wave that reaches the breakwater is 2.6m. But this model does not take into account the sea level elevation (wind set-up, wave set up) due to storms. Measurements during hurricane Michelle indicated a sea level elevation of 1.5m. So a new calculation has to be made for the wave height reaching the breakwater.

In order make a better estimation, a breaker index $\gamma$ of 0.8 has been used. So the wave height can not exceed a value of 0.8 times the actual depth, because then the wave would have been already broken in front of the structure. Placing the breakwater at a depth of 4.1 m under MSL, with an elevation of 1.5m, gives a maximum depth of 5.6m. Using a value of $\gamma=0.8$, the maximum wave height that reaches the structure is 4.4m. The period of this wave is 8.0s. The wave length in front of the breakwater at 500m from the shore is 55.3m.
The damage level $S$ is defined by Van der Meer (1988) and will be of the value $S = 2$ (start of damage).

The density $\rho_w$ for the concrete cubes is taken 2400 kg/m$^3$.

The results of the nominal grain size during stormy conditions are presented in table 11-1.

<table>
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<tr>
<th>$h_c$</th>
<th>$H_s$</th>
<th>$L$</th>
<th>$s_p$</th>
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<th>$S$</th>
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<td>2.00</td>
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<td>0.68</td>
</tr>
</tbody>
</table>

Table 11-1 Results calculation $D_{n50}$; stormy conditions

This means that concrete cubes of 0.68m are sufficient to provide stability.

**11.4.2.3 Stability of the layer under normal conditions**

The wave attack will be highest when there is no set-up due to wind or waves. This occurs in the normal situation. Figure 11.1 shows that the maximum wave height is 2.6 m. This wave has a period of 6.5 s and a wavelength of 44.5 m.

With formula 11.1 the $D_{n50}$ is calculated for normal conditions and shown in table 11-2.

<table>
<thead>
<tr>
<th>$h_c$</th>
<th>$H_s$</th>
<th>$L$</th>
<th>$s_p$</th>
<th>$h$</th>
<th>$S$</th>
<th>$\Delta$</th>
<th>$D_{n50}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.80</td>
<td>2.60</td>
<td>44.50</td>
<td>0.06</td>
<td>4.00</td>
<td>2.00</td>
<td>1.34</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Table 11-2 Results calculation $D_{n50}$; normal conditions

**11.4.2.4 Conclusion of the nominal grain size diameter**

Comparing the results of the normal and stormy conditions, the conclusion is drawn that in the next paragraphs the calculations will be made with a nominal grain size diameter of 0.68 m. This is so because the value of 0.68 m during stormy conditions is higher than the value of $D_{n50}$ during normal conditions ($D_{n50}=0.63$ m).

**11.4.3 Determination of the crest width and slope**
According to CUR 169\(^1\) the crest width should be sufficient to permit at least 3 stones to be placed in the crest. The required nominal grain size diameter is 0.68 m, so the crest width should be at least 2.04 m. In order to make a conservative estimation a crest width of 4 stones (2.72 m) is chosen.

The outer face of the breakwater has a slope of 1:3 to reduce reflective scour and increase energy dissipation. The rear face can be steeper but will be taken 1:3 as well.

11.4.4 Dimension of the layers

In this paragraph the composition of the breakwater is designed. This means that the layer thickness and the under layers and core will be determined.

11.4.4.1 Dimension of the outer layer

The fifty percent passing nominal diameter (\(D_{n50}\)) is the size of the cube equivalent volume to the block of medium mass and is given by:

\[
D_{n50} = \left(\frac{W_{50}}{P_r}\right)^{1/3}
\]

Formula 11.2

\(D_{n50}\) Nominal grain size diameter (m)
\(W_{50}\) Block mass (kg)
\(P_r\) density of the cube (kg/m\(^3\))

<table>
<thead>
<tr>
<th>(D_{n50}) (m)</th>
<th>(P_r) (kg/m(^3))</th>
<th>(W_{50}) (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.68</td>
<td>2400</td>
<td>755</td>
</tr>
</tbody>
</table>

For a maximum \(D_{n50}\) of 0.68 m, the \(W_{50}\) should at least be 755 kg.

11.4.4.2 Layer thickness

The layer thickness (t) can be calculated with formula 11.3 according to the Shore Protection Manual (1984) and CUR/CIRIA (1991). For the \(K_s\) values,

\[
t = m \cdot K_s \cdot D_{n50}
\]  

(Formula 11.3)

---

\(^1\) Manual on the use of rock in Hydraulic Engineering
with:
\[ t \] layer thickness (m)
\[ m \] number of layers of armour units (-)
\[ K_a \] layer thickness coefficient (-)
\[ D_{n50} \] nominal diameter of the cube (m)

With a \( K_a = 1.1 \) and 2 layers of Concrete cubes

<table>
<thead>
<tr>
<th>( m ) (m)</th>
<th>( K_a ) (-)</th>
<th>( D_{n50} ) (m)</th>
<th>( t ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.1</td>
<td>0.68</td>
<td>1.50</td>
</tr>
</tbody>
</table>

### 11.4.4.3 Underlayer and Core

When the same material is used, the underlayer may consist of units with a weight of 1/15 to 1/25 of the block weight in the layer above it, provided the stability during construction permits it\(^2\). When quarries are used with a concrete or quarry-rock layer above it, stones can be used of 1/11 of the block weight\(^3\). The most conservative values will be used for the required blocks.

A relatively large underlayer (core) has two advantages. First, the surface is less smooth with larger stones and this gives more interlocking with the armour. This is especially the case if the top layer is constructed of concrete units. Secondly, a large under-layer results in a more permeable structure and therefore has a large influence on the stability of the top layer.

With a \( p_r = 2200 \text{ kg/m}^3 \) and \( K_a = 1.00 \) for quarry rock of 2 layers, the total structure is given in table 11-3.

<table>
<thead>
<tr>
<th></th>
<th>( p_r ) (kg/m(^3))</th>
<th>( D_{n50} ) (m)</th>
<th>( W_{50} ) (m)</th>
<th>( T ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>2400</td>
<td>0.68</td>
<td>755</td>
<td>1.50</td>
</tr>
<tr>
<td>Layer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core</td>
<td>2200</td>
<td>0.31</td>
<td>70</td>
<td>1.30</td>
</tr>
</tbody>
</table>

**Table 11-3 Composition of the breakwater**

---

\(^1\) Layer coefficient and porosity of different armour units, Shore protection Manual, (1984)


\(^3\) SPM, 1984 and CUR/CIRIA, (1991)
To get an idea of the composition of the breakwater a cross-section is given in figure 11-14. The height of the breakwater is only 2.8 m, so it is a small breakwater. That is why it is also possible to build it up by different layers of the same material. In this project the design of the breakwater is made by following the method of project group CF06 (Havana city wall).

![Cross-section of the breakwater](image)

**Figure 11-14 Cross-section of the breakwater**

### 11.4.4.4 Breakwater toe

If the cubes in the toe have the same dimensions as the armour, the toe will be stable. But it is more economical to reduce the size of the cubes\(^1\). Formula 11.3 can be used.

\[
\frac{H_s}{\Delta \cdot D_{n50}} = 8.7 \cdot \left( \frac{h_t}{h_m} \right)^{1.4}
\]

**Formula 11.3**

With

- \(H_s\) Significant wave height (m)
- \(\Delta\) Relative density: \(\frac{\rho_s - \rho_w}{\rho_w}\) (-)
- \(D_{n50}\) nominal diameter of the cube (m)
- \(h_t\) depth above the toe (m)

\(^1\) CUR/CIRIA, (1991)
\( h_m \)  depth before the breakwater (m)

The validity of this equation is restricted to situations with little damage (\( S = 2 \) this means start of damage) and relatively deep toes (\( h_d/h_m > 0.4 \)). If the same cubes are used as for the core of the breakwater, with a \( D_{50} \) of 0.31m the production costs of the cubes will be reduced. The height of the toe can now be determined and is approximately 1.30m. The toe will be constructed in two layers of concrete cubes with a \( D_{50} \) of 0.31m.

The used method to calculate the breakwater toe leads to a determination of the toe of 1.3m. The height of the breakwater is just 2.8 meters, so the toe would be relatively large. This is unacceptable, that is why for this project it is chosen to leave the breakwater toe away. This is done after consultation with the tutors of the ISPIAE.

### 11.4.4.5 Breakwater head

When a wave is forced to break over a round head it leads to large velocities and wave forces. For a specific wave direction only a limited area of the head is highly exposed. The weight of the armour will be increased to obtain the same stability as for the trunk section. No specific rules are available for the breakwater head. The required increase in weight can be a factor between 1 and 4, depending on the type of armour unit. The Shore Protection Manual (1984) recommends constructing a head with cubes that are twice as heavy as in the trunk (table 11.4). The under-layer will also have a different cube size according to Paragraph 11.3.2.3.

<table>
<thead>
<tr>
<th></th>
<th>Trunk</th>
<th>Head</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_{50} ) top-layer</td>
<td>0.68m</td>
<td>1.55m</td>
</tr>
<tr>
<td>Weight cube top-layer</td>
<td>755kg</td>
<td>3020kg</td>
</tr>
<tr>
<td>( D_{50} ) under-layer</td>
<td>0.31m</td>
<td>0.51m</td>
</tr>
<tr>
<td>Weight cube under-layer</td>
<td>70kg</td>
<td>300kg</td>
</tr>
</tbody>
</table>

**Table 11-4 \( D_{50} \) of the breakwater head**
11.5 *Construction method*

The construction of the breakwater has to be done with floating equipment as the breakwater is not connected to the shore and will be submerged. Local floating equipment is preferred to construct economically and create local employment. No dumping vessels are available, but floating cranes can place the cubes. For the small breakwater one floating crane may be enough to construct the breakwater in a reasonable time, but for the larger breakwater it is necessary to use several floating cranes. The other floating material should be a pontoon with a derrick or a crane, because with this type of equipment it is possible to place small quantities of stone each cycle, or larger stones placed individually. Bed protection for bridge abutments is an example where stones should be placed in small quantities. In this case the cranes are used for accurate placement of larger material. This means that the cubes are placed piece by piece to construct a two layer system of the breakwater.

To place the material it is possible to have the crane on the same vessel as the material, but it is also possible that the crane is placed on a separate pontoon and the material is moved by another vessel (barge). By using the separate method the dumping process is not interrupted and when using several vessels to transport the material the total constructing time will be reduced. The transport of the concrete cubes from the factory to the barges will be done by trucks.

**Operational site conditions**

For this kind of waterborne operations the following site conditions will have to be considered:

- Current, wave and wind conditions
- Available water depth and maneuvering space
- Seasonal influences
- Shipping
- Tidal variation
- Visibility

*Current, wave and wind conditions*

The positioning of the ship should not give a problem, because the currents are weak. The wave and wind conditions during the proposed construction interval (April-September) may cause many problems.
Available water depth and maneuvering space
The bottom slope is very mild (1:40) and the depth is 4.3m, that is why no major difficulties are expected during the construction.

Seasonal influences
Due to the tourist season and the storm season the construction is only allowed to take place between April and September. It should not be a problem to construct the breakwaters within six months.

Shipping
There is no shipping allowed near the coast of Varadero so no hindrance will be expected; this is a positive aspect concerning the total construction time.

Tidal variation
Dumping is preferably carried out around slack tide. Due to the small tidal difference (approximately 0.2m) in this area the tidal variation's influence is not of any significance.

Visibility
The visibility in the region should not give any problems, because the water is quiet clear and the bottom level is situated just 4.3m below sea level.

11.6 Costs
In this Paragraph the costs are determined for the hard type solution. There are two alternatives presented when using a hard type solution;
One alternative with a breakwater of just 200m, and another alternative with a breakwater along almost the whole coast of the critical zone. The costs for both alternatives are presented separately. The calculation of the costs is presented in appendix 23.

11.6.1 Costs of a Breakwater of 200 m
The costs of the total project of a breakwater of 200m with nourishment and maintenance with sands in 50 years consist of:
- Construction of a breakwater of 200m
- Initial nourishment of about 404.500m³ sand
- Every 5 years (counted from the moment of the initial nourishment) a maintenance nourishment of about 112.600m³ sand
- Every 5 year a movement of 66.900m³ sand over a distance of about 800 m

The total costs of this solution are in 50 years are given in the table below (table 11-5) (taking into account the discount rate based upon Dutch standards):

<table>
<thead>
<tr>
<th>Year</th>
<th>Action</th>
<th>Costs at that year</th>
<th>Factor</th>
<th>Cost at year 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Construction of Breakwater</td>
<td>$2.119.562</td>
<td>1.00</td>
<td>$2.119.562</td>
</tr>
<tr>
<td>0</td>
<td>Initial nourishment</td>
<td>$671.357</td>
<td>1.00</td>
<td>$671.357</td>
</tr>
<tr>
<td>5</td>
<td>Maintenance 1</td>
<td>$262.918</td>
<td>0.78</td>
<td>$205.076</td>
</tr>
<tr>
<td>10</td>
<td>Maintenance 2</td>
<td>$262.918</td>
<td>0.61</td>
<td>$160.380</td>
</tr>
<tr>
<td>15</td>
<td>Maintenance 3</td>
<td>$262.918</td>
<td>0.48</td>
<td>$126.200</td>
</tr>
<tr>
<td>20</td>
<td>Maintenance 4</td>
<td>$262.918</td>
<td>0.38</td>
<td>$99.909</td>
</tr>
<tr>
<td>25</td>
<td>Maintenance 5</td>
<td>$262.918</td>
<td>0.29</td>
<td>$76.246</td>
</tr>
<tr>
<td>30</td>
<td>Maintenance 6</td>
<td>$262.918</td>
<td>0.23</td>
<td>$60.471</td>
</tr>
<tr>
<td>35</td>
<td>Maintenance 7</td>
<td>$262.918</td>
<td>0.18</td>
<td>$47.325</td>
</tr>
<tr>
<td>40</td>
<td>Maintenance 8</td>
<td>$262.918</td>
<td>0.14</td>
<td>$36.808</td>
</tr>
<tr>
<td>45</td>
<td>Maintenance 9</td>
<td>$262.918</td>
<td>0.11</td>
<td>$28.921</td>
</tr>
<tr>
<td></td>
<td>TOTAL COST</td>
<td></td>
<td></td>
<td>$3.600.000</td>
</tr>
</tbody>
</table>

Table 11-5 Costs of a 200m breakwater

11.6.2 Costs of a breakwater of 1200 m

The costs of the total project of a breakwater with nourishment in 50 years consist of:

- Construction of a breakwater of 1200 m
- Initial nourishment of about 173.100m³ sand
- A maintenance nourishment every 5 year (measured from the initial nourishment) of 46.000m³
- Every 5 year a movement of 68.500m³ sand over a distance of about 800 m

The total costs of this solution in 50 years are given in the table below (table 11-6) (taking into account the discount rate based upon Dutch standards):
<table>
<thead>
<tr>
<th>Year</th>
<th>Action</th>
<th>Costs at that year</th>
<th>Factor</th>
<th>Cost at year 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Construction of Breakwater</td>
<td>$11,490.330</td>
<td>1.00</td>
<td>$11,490.330</td>
</tr>
<tr>
<td>0</td>
<td>Initial nourishment</td>
<td>$432.077</td>
<td>1.00</td>
<td>$432.077</td>
</tr>
<tr>
<td>5</td>
<td>Maintenance 1</td>
<td>$181.167</td>
<td>0.78</td>
<td>$141.310</td>
</tr>
<tr>
<td>10</td>
<td>Maintenance 2</td>
<td>$181.167</td>
<td>0.61</td>
<td>$110.512</td>
</tr>
<tr>
<td>15</td>
<td>Maintenance 3</td>
<td>$181.167</td>
<td>0.48</td>
<td>$86.960</td>
</tr>
<tr>
<td>20</td>
<td>Maintenance 4</td>
<td>$181.167</td>
<td>0.38</td>
<td>$68.843</td>
</tr>
<tr>
<td>25</td>
<td>Maintenance 5</td>
<td>$181.167</td>
<td>0.29</td>
<td>$52.538</td>
</tr>
<tr>
<td>30</td>
<td>Maintenance 6</td>
<td>$181.167</td>
<td>0.23</td>
<td>$41.668</td>
</tr>
<tr>
<td>35</td>
<td>Maintenance 7</td>
<td>$181.167</td>
<td>0.18</td>
<td>$32.610</td>
</tr>
<tr>
<td>40</td>
<td>Maintenance 8</td>
<td>$181.167</td>
<td>0.14</td>
<td>$25.363</td>
</tr>
<tr>
<td>45</td>
<td>Maintenance 9</td>
<td>$181.167</td>
<td>0.11</td>
<td>$19.928</td>
</tr>
<tr>
<td></td>
<td>TOTAL COST</td>
<td></td>
<td></td>
<td>$12,500.000</td>
</tr>
</tbody>
</table>

Table 11-6 Costs of a 1200m breakwater

The costs are presented in Appendix 24.
11.7 Summary

In this chapter an offshore, submerged breakwater is designed as hard-type solution of the erosion problem. A breakwater is used to change the climate near the beach. With the aid of the UNIBEST model which uses the ENDEC\textsuperscript{1} wave model an assumption is made to determine the location of the breakwater. The conclusion is that the waves of 1.5m, 2.5m and 3.5m cause a large part of the erosion. In order to let these waves break on the breakwater, the location is fixed 500m offshore on the second sand bank. The bottom level is approximately 4.3m below the water surface.

In this chapter two offshore submerged breakwaters are designed, one breakwater of 200m length and a second 1200m long.

Considering the bill of demands, the breakwater should not be visible from the beach that is why the crest height is determined on 2.8 m. The top of the breakwater is now approximately 1.5m below mean sea level.

To determine the other dimensions of the breakwater some parameters had to be determined first, e.g. nominal grain size diameter, type of material, number of layers, thickness of the layers, slope etc. The determination of the composition of breakwater is only roughly made. Results are presented in table 11-7.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest width</td>
<td>2.72 m</td>
</tr>
</tbody>
</table>
| Crest height      | 2.80 m| Above bottom level
| Slope             | 1:3   | Inner and outer face
| Outer layer (Dn50)| 0.68m | Layer thickness is 1.5m; Concrete cubes
| Inner layer (Dn50)| 0.31 m| Layer thickness is 1.3m; Quarries

\textbf{Table 11-7 Dimensions submerged breakwater design}

\textsuperscript{1} (Prof.dr.ir. Battjes and Prof.dr.ir. Stive, TUDelft 1974)
Cross-section of the breakwater

The breakwater will be constructed with the aid of floating equipment and is advised to be carried out in the months April-September, because of the optimal (marine) climate circumstances.

The cost estimation is not only based upon the dimensions and construction of the breakwaters, but on the extra beach nourishment program as well. This program is needed to prevent the coastal retraction in 50 years.

The costs of a 200m breakwater with nourishment and maintenance with sands in 50 years are 3.6 million dollars and consist of:
- Construction of a breakwater of 200m
- Initial nourishment of about 404.500m³ sand
- Every 5 years (counted from the moment of the initial nourishment) a maintenance nourishment of about 112.600m³ sand
- Every 5 year a movement of 66.900m³ sand over a distance of about 800 m

The costs of the total project of a 1200m breakwater with nourishment in 50 years consist of:
- Construction of a breakwater of 1200 m
- Initial nourishment of about 173.100m³ sand
- A maintenance nourishment every 5 year (measured from the initial nourishment) of 46.000m³
- Every 5 year a movement of 68.500m³ sand over a distance of about 800 m
12 Methodology

This chapter proposes a methodology for further coastal protection on the Peninsula de Hicacos and handles the methodology that was followed in this research. First, the general approach of future erosion problems of the peninsula is handled. Afterwards, it is specified for the research conducted on the peninsula.

12.1 Decision to intervene

The coast line along Cuba and especially near Varadero is monitored continuously. In the case of Varadero, this is done by the Institute of Oceanology. When a movement of the coastline is measured, either in forward or backward direction, the decision tree in figure 12-1 should be followed. In this tree, different colors are used:

- blue marks Questions that need to be answered
- gray marks Answers to these questions and observations
- pink Actions that follow from the decision tree

Because the movement of the coast can change in time, the use of this tree should be repeated regularly for all beaches on the peninsula.
12.2 General approach of intervention

When the decision is made that actions have to be taken, the process reflected in figure 12-2 should be followed.
At first, the occurring problems have to be analyzed and identified. Important in this phase is the identification of the causes of the problems and to get a good view of the impact of the problems. A clear problem definition and estimation of consequences has to be made. See figure 1-3.

After the problem analysis, alternatives have to be elaborated. Weighting criteria have to be determined and for example with the use of a Multi Criteria Analyses a choice has to be made which alternatives are taken in further research. A pre-design
will be made of these alternatives, and afterwards a final choice will be made what alternative or combination of alternatives are the best. This alternative will be put into practice.

For this alternative or combination of alternatives, a final draft is made and execution can take place. After the execution has finished, an evaluation of the total project has to be made. This evaluation is made to see if the project went well, but it is also done to improve further projects.

### 12.3 This research

In this research, the necessity for actions was indicated by the ISPJAE, the Havana University of Technology. Despite the nourishment activity in 1998, a regression of the coast line was measured by the Institute of Oceanology at some places along the coast and on some places on the peninsula the safety of structures on the dunes is in danger. Also, at some places, the beach has become too narrow so that not enough dry beach was present for recreational activities. Intervention is needed.

#### 12.3.1 Chronological approach of the research

First of all, the theory of morphological processes was studied as it forms the necessary input for the study. Most coastal data was obtained from the Institute of Oceanology, the ORPV, and CISAM, though also other sources were used like internet.

In a brainstorm, a list of possible causes of erosion was made, and afterwards the possible causes were divided in five groups. For every possible cause, it was determined if it could play a role in the erosion problems on the Peninsula de Hicacos. If the cause was suspected to play a significant role in the erosion, the possible causes were quantified to determine their contribution to the erosion.

The importance of the beaches of the peninsula was very clear from the beginning, as Varadero is of large importance to the national income of Cuba. Hardly any information about Cuban norms was available, only an article on coastal zone management legislation was found.
With several models like UNIBEST and CRESS the size and nature of the erosion was determined.

After the modeling of the erosion of the whole peninsula, the most critical zone was determined. For this zone, alternatives were generated in a brainstorm session. Based on another brainstorm, a list of demands was made in order to limit the problem.

The alternatives were weighted in a Multi Criteria Analyses and alternatives were pre-designed. No final decision about the best alternative was made. This final decision should be made by Cuban authorities.
13 Conclusions and Recommendations

The main objective of the project was to get an analysis of the erosion and to find a way to protect the Peninsula de Hicacos from future structural erosion that it is threatened by. The following conclusions are drawn:

13.1 Conclusions

Final Conclusions:

- Causes of the structural erosion for the whole peninsula:
  - Longshore transport gradients (varies along the peninsula between 89,000 and 134,000 m\(^3\) per year, computed in a longshore computer model called UNIBEST)
  - Wind (maximum of 175,000 m\(^3\) in the direction of the dunes each year. Further research necessary)
  - Global sea level rise (11.500 m\(^3\)/year)

- Three critical zones on the peninsula can be identified where the erosion is most severe, these are:
  - Paso Malo breakwater - Hotel Oasis
  - Calle 20-37
  - Palacio de la Rumba - Punta Chapelin

- Causes of erosion for the most critical zone Calle 20-37:
  - Longshore transport gradients (16,320 m\(^3\)/year)
  - Cross-shore transport (38,000 m\(^3\))
  - Sea level rise (2130 m\(^3\)/year)

Soft type solution:

- Nourishment:
  - Extension of the dry beach zone with 15m and fix for 50 years to come
  - Borrowing zone: Cayo Mono at a distance of 10 km from the zone
- Location: On the foreshore and beach of the critical zone
- Amount initial nourishment: 465,000 m³
- Maintenance nourishment of 165,000 m³ every 5 years
- Execution: sand extracted with a trailing suction hopper dredger, nourished on the foreshore and beach by booming
- Costs of USD 1,800,000 for the nourishment program taken into account a discount rate of 5%

Hard type solutions:
- Submerged offshore breakwater of 200 m:
  - With initial nourishment of 404,500 m³
  - With maintenance nourishment of 112,600 m³ every 5 years
  - Movement of 67,000 m³ within the critical zone every 5 years
  - Costs of USD 3,600,000 for the construction of the breakwater, the initial nourishment and the maintenance program taken into account a discount rate of 5%
- Submerged offshore breakwater of 1200 m:
  - With initial nourishment of 173,100 m³ every 5 years
  - With maintenance nourishment of 46,000 m³ every 5 years
  - Movement of 68,500 m³ within the critical zone every 5 years
  - Costs of USD 12,500,000 for the construction of the breakwater, the initial nourishment and the maintenance program taken into account a discount rate of 5%

Methodology
- A methodology to deal with erosion problems at the Peninsula of Hicacos is presented

13.2 Recommendations

- Profile measurements have to be done in the whole dynamic zone.
- More research has to be done to determine the whole wave climate, including measurements of directions.
- A study has to be done to determine the amount of sand production of the Algae Halimeda fields.
- More up to date information about availability and costs of construction material and equipment is necessary.
An investigation has to be done to make a description of the actual velocity current distribution in long shore directions.

More sections should be used in UNIBEST where the transport capacity is defined.

The bottom roughness should be measured at different locations to come to a mean value.

Further investigation about the influence of winds on the sediment transport is needed.

Cross shore calculation should be done with a model that is applicable for a mild beach slope and normal conditions.

An investigation about the amount of sand that can be extracted at the east side of the Paso Malo has to be carried out.

Further research has to be done after the location and orientation of the offshore submerged breakwaters.

The wave climate behind an offshore submerged breakwater needs better investigation, as well as the determination of the crest height. This could be done by a physical model in a laboratory.

A study to prevent erosion on the entire peninsula should be carried out.
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Chart nr. 3867

Chart nr. 410

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Erosion of the Peninsula de Hicacos, Varadero

Quantification of the potential sediment transport and possible solutions

APPENDICES

Havana, Cuba
4 September – 31 November 2003

FINAL REPORT

Authors:
C.A.J. van Dam
M.D. van Dijk
R.F. Lausman
R.W.J. Over
T.J. Segboer

Supervisors:
Cuba
Dr. ir. L. Córdova López
Msc. R.T. Hugues

The Netherlands
Prof. dr. ir. M.J.F. Stive
Dr. ir. J. van de Graaff
Ing. G.A. Beaufort
Ir. I.J. Zwemer
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Figure 1-3 Historic Varadero
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Profile Section 1

Figure 2-2 Profile Section 1
Figure 2-3 Profile Section 2

Figure 2-4 Profile Section 3
Profile Section 4

Distance from measurement point (m)

Figure 2-5 Profile Section 4

Profile Section 5

Distance from measurement point (m)

Figure 2-6 Profile Section 5
Figure 2-7 Profile Section 6
3 Appendix: Comparison of the sand samples taken along the nourishment zone of 1998

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<td>Medium</td>
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Md: Mean diameter

Table 3-1 sand samples
4 Appendix: Fall velocity of quartz spheres in air and water

5 Appendix: Legislation regarding coastal limits

5.1 Low terrace

This type of coast constitutes of calcareous rocks, including a storm ridge of loose materials such as gravel and sand formed during storms and regularly covered by vegetation. If the storm ridge is not present the coastal zone limit will extend 20 m land inwards from the start of the vegetation. In case of a rock cliff on the low terrace located less than 20 m from the start of the vegetation. The limit of the coastal zone will extend until the rock cliff.

Figure 5-1 Coastal Zone limits for Low terrace
If the area adjacent to the low terrace is a coastal lagoon with mangroves see section D of this article.

5.2 Rocky cliffs

Rocky cliffs are defined as: Rocky cliffs that are not inundated during high tides. The coastal zone extends 20 m from the top of the cliff.

![Coastal Zone limit](image)

Figure 5-2 Coastal Zone limits for Rocky cliffs

5.3 Beaches

Beaches are defined as: The area where loose materials are deposited such as sand and gravel. Underwater banks, berms and dunes are also included. The coastal zone extends until the interior side of the dune nearest to the sea. If a dune is not present the limit will be 40m land inwards from the start of the vegetation, if a cliff is present the limit given by the top of the cliff.

If the area adjacent to the dune or the berm, is a coastal lagoon with mangroves see section D of this article.
Figure 5-3 Coastal Zone limits for Beaches

5.4 Mangrove

Mangroves are defined as: The area constituted by mangroves associated with coastal lagoons and in general low terrain which is under influence of flow by tides, waves or infiltration of seawater. The limit of the coastal zone is given by the maximum penetration of the mangrove forest.
Coastal zone limit: maximum penetration of mangrove forest

Coastal zone limit: maximum penetration of mangrove forest landinwards

coastal zone limit: maximum penetration of mangrove forest

Figure 5-4 Coastal Zone limits for Mangroves

If the identification of the types of coasts is not possible the coastal zone limit will reach until where the highest waves known have reached.

The Decreto-Ley Article 4 states that the limit of the coastal zone towards the sea extends until the border of the peninsular platform.

5.5 Coastal Protection Zone

The Cuban coastal legislation also defines a Coastal Protection zone, which is defined as a dampening zone for human activities with the objective to satisfy needs of transport public service and safety.

The Coastal Protection Zone for the different coast types are:

A: Low terrace: a minimal limit of 25m land inwards measured from the Coastal Zone limit
6 Appendix: Global Wave Statistics

6.1 Area 32
### 6.2 Directions taken into account

#### WEST

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<th>6-7</th>
<th>8-9</th>
<th>10-11</th>
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Percentage of OBS = 3.29%

#### NORTH WEST

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Percentage of OBS = 4.93%
Longshore current distribution (N)

Longshore Current velocity distribution (NW)

Longshore velocity distribution (W)

Table 7-1 Local velocity distributions used in BIJKER
# 8 Appendix: Computation in CERC

The amount of potential sediment transport calculated with CERC and one weighted wave per direction is showed in figure 1.

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<th>hv0</th>
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<th>tanh(h0)</th>
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<th>Kri</th>
<th>Ks</th>
<th>Hb</th>
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<td>phi</td>
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<td>d/0</td>
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Figure 8-1 calculation amount of sediment for one weighted wave per direction

The amount of potential sediment transport calculated with CERC for the whole wave climate is showed in figure 2.

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<th>T</th>
<th>Ao</th>
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**Total** 500.516
## 10 Appendix: Computations in BIJKER

The amount of potential sediment transport calculated with BIJKER for the four representative waves and the original velocity distribution is shown in Table 9-1.

### North East

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<th>Tcw</th>
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### Notes:

- Y: Distance from the mouth of the river (m)
- h: Water depth (m)
- C90: Coefficient for 90% flow
- C: Coefficient for 50% flow
- Mu: Momentum number
- L: Length of the reach (m)
- k: Froude number
- Limit H: Limit height (m)
- Eta: Eta number
- Ub: Bed friction number
- a0: Arithmetic mean of the water depth (m)
- Johnsr Bijker: Johnsr Bjikjer number
- Y: Y-coordinate
- Tcw: Total sediment transport (kg/s)
- V: Velocity (m/s)
- Z: Depth (m)
- r/h: Ratio of the reach length to the bed width
- Sb: Bed slope
- Q: Sediment discharge (m^3/s)
- Ss: Sediment discharge (m^3/s)
- Sediment: Sediment type

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Project group CF015

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-1.020,040
### Table 10-1 Computations using original velocity distribution

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\(-1,136,992\)
The amount of potential sediment transport calculated with BJKER for the four representative waves and the Lengoulet Higgins velocity distribution is shown in Table 9-2.

Table 10-2 Computation using Longuet Higgins velocity distribution


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Appendices

Project group CF015

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11 Appendix: Results of QUEENS-formula

The next table shows the in- and output parameters from the QUEENS-calculation with four wave, one from each direction.

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Table 11-1 Results from four waves only

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Figure 11-1 Results for the Western direction
### Peninsula de Hicacos

#### Appendices

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<td>5.29</td>
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</table>

Total: -0.86 -24.498

**Figure 11-2 Results from the North Western direction**

### North

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<th>Ps</th>
<th>2650</th>
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<th>Hs</th>
<th>T</th>
<th>Ao</th>
<th>Occurency</th>
<th>Co</th>
<th>Lo</th>
<th>Ab</th>
<th>2Ab</th>
<th>Hb</th>
<th>S (m3/s)</th>
<th>S (m3/yr)</th>
</tr>
</thead>
<tbody>
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<td>0.06</td>
<td>14893.16</td>
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Total: 0.92 66.664

**Figure 11-3 Results from the Northern direction**

### Northeast

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<th>Northeast</th>
<th>Hs</th>
<th>T</th>
<th>Ao</th>
<th>Occurency</th>
<th>Co</th>
<th>Lo</th>
<th>Ab</th>
<th>2Ab</th>
<th>Hb</th>
<th>S(M3/s)</th>
<th>S(M3/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ro</td>
<td>1025</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D50</td>
<td>0.0003</td>
<td>18.19</td>
<td>7.50</td>
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</tr>
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<td>0.001091</td>
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<td>3.03</td>
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</tr>
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<td>0.50</td>
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<td>0.068758</td>
<td>7.27</td>
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<td>0.56</td>
<td>0.35</td>
<td>0.00</td>
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</tr>
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</table>

Total: 0.30 49,380

**Figure 11-4 Results from the North Eastern direction**
12 Appendix: Short explanation on

the use of UNIBEST

12.1 Introduction

To calculate the sediment transport (long shore) along the coast of the Hicacos Peninsula the software modules UNIBEST LT (Long shore Transport) and UNIBEST CL (Coastline development) are used. UNIBEST LT can calculate the amount of sediment transport due to wave and current conditions, and the data from these calculations are used in UNIBEST CL to predict how the coastline will develop for a certain period and how that affects the local transport.

The way UNIBEST works is explained shortly as is the input needed and the output produced.

12.2 UNIBEST LT

UNIBEST LT is designed to calculate the sediment transport over a cross shore profile. In order to do so, the program uses different input to calculate the transport in a so called ray (a beach area, in Dutch: "raal"). So a transport ray is a value for the amount of sediment transported due to several components in a certain area. Also the distribution of the sediment transport over the section is computed as is the velocity near the bottom and the refraction of the wave front towards the coast.

12.3 Input UNIBEST LT

The transport rays depend on the following components:

- The wave and current conditions:
  - The wave upset of the waterline
  - Significant wave height
  - Wave period
  - Wave angle of approach from deep water
  - The chance of occurrence of the wave during one year (in hundredths of a day).
- Tidal information, such as mean amplitude and velocities.
  - The wave parameters consisting of:
    - wave breaking coefficients
    - bottom friction coefficients
    - bottom roughness
  - The cross shore profile with specifications:
    - boundary of the dynamic profile
    - boundary of the truncation transport
    - depth of the bottom at certain distances from the coastline
  - The transport parameters. A choice can be made between three different formulae to calculate the sediment transport along the cross shore profile, namely:
    - Cerc (1984)
    - BIJKER (1967, 1971)
    - Van Rijn (1992)

12.4 Output UNIBEST LT

The output of UNIBEST LT is given in different forms. Different variables can be plotted in graphs which vary along the cross shore profile such as the $H_o$, the wave angle and the $Q_{sediment}$ for example.

The values of the transport (rays) can be found which can be used to calculate the total sediment transport (and its distribution) in a certain area. The rays are used in UNIBEST CL.

12.5 UNIBEST CL

With UNIBEST CL one can use the results calculated in UNIBEST TC to apply on a coast area where the wave and current characteristics are known. A model of the coastal area can be drawn (like a map viewed from above) and with all parameters a prediction can be made how the coast will develop in the years to follow. For that the program uses several calculation steps to determine the local transport for every ray (in the model, the total number of rays is 125). The dynamic process of erosion and accretion can be viewed numerically (at beforehand appointed different time points) as well as graphically (real time during which the process can be stopped and output printed in reports).
12.6 Input UNIBEST CL

The input in UNIBEST CL consists of:

- The coordinates of a basic model. This forms a map of the beach area that is looked at. This can be done from basic points behind the beach, from where the distance to the beach is defined. Interpolation between the basic points gives an fluent curve to the beach if necessary. Between the basic points one can declare in how many compartments this sections has to be divided.

- The assignment of different (already in UNIBEST TC calculated) rays to different sections of the coast.

- A console where some parameters of a ray can be modified if necessary.

- The boundary conditions at both ends of the drawn beach section. Different conditions can be chosen to reflect the reality, such as:
  - The coastal angle can't change
  - The coordinates of the boundary can't change (no re- or transgression of the coast at the boundary)
  - The sediment throughput is constant
  - The sediment throughput is variable according to a function known through measurements.

There is also the possibility to model the different possible extra conditions in the coastal zone, such as:

- Groins, to model breakwaters and such, with different possible blocking percentages

- Offshore breakwaters, these are not used for calculations: one has to determine the wave climate behind it oneself (the transport ray will be different locally)

- Revetments to model a seawall which prevents erosion of the coast in that area

- Sources and sinks to model rivers that put sediment in the system or other sources such as eroding cliffs or reefs or beach nourishments. The sinks can be used to simulate sand extraction for example

- Internal boundaries have the same principals as groins, but can be used to indicate local irregularities. If the length of the internal boundaries is considered long enough (to block the total area of transport) and the blocking percentage is set to 0%, the sediment can pass, but the amount is determined by the coastal angle on the 'upstream' side only, not by the coastal angle over the boundary as is the case with a breakwater (so no local rays can be defined).
13 Appendix: Transport rays in the basic model

Transport rays in the basic model for 4 waves and all waves both calculated with CERC and BIJKER.

13.1 CERC: 4 waves

![Diagram with overlay text](image)

Figure 13-1 The results for the basic model using CERC and 4 waves
13.2 BIJKER: 4 waves

Figure 13-2 The results for the basic model using BIJKER and 4 waves

13.3 CERC: all waves

Figure 13-3 The results for the basic model using CERC and all waves
13.4 BIJKER: all waves

![Diagram showing wave profiles and transport rates]

Figure 13-4 The results for the basic model using BIJKER and all waves
Velocity distribution

**Section 2**

Wave on deep water: \( H_s = 1.5 \), wave angle = 60

Profile section 2

Transformation of \( H_s \)
Transformation of the wave angle

Velocity distribution

Section 3

Wave on deep water: $H_s = 2.5$, wave angle = -30
Profile section 3

Transformation of $H_s$
Transformation of the wave angle

Velocity distribution

Section 4

Wave on deep water: $H_s = 3.5$, wave angle = 15

Profile section 4
Transformation of $H_s$

Transformation of the wave angle
Velocity distribution

**Section 5**

Wave on deep water: $H_s = 4.5$, wave angle = -75

Profile section 5

Transformation of $H_s$
Transformation of the wave angle

Velocity distribution

Section 6

Wave on deep water: $H_s = 5.5$, wave angle = -60
Profile section 6

Transformation of $H_s$
Transformation of the wave angle

Velocity distribution
15 Appendix: Cross-shore sediment transport results

![Profile Section 3](image)

Figure 15-1 Profile section with trend line

**Hurricane Michelle**
Next Table and Figure belong to the computation (Excel) of the consequences of the Hurricane “Michelle”.

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<th>Unknown</th>
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</thead>
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<tr>
<td>$M_o$</td>
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</tr>
<tr>
<td>$g$</td>
<td>9.81</td>
</tr>
<tr>
<td>$S_{max}$</td>
<td>1.5</td>
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<tr>
<td>$T_d$</td>
<td>12</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 15-1 Hurricane Michelle
In which:

hb = Breaking depth (m)
HB = Breaking wave height (m)
D = Grain size (m)
B = Berm height (m)
M0 = Beach slope (-)
G = Gravitational acceleration (m/s²)
Smax = Maximum sea level elevation (m)
Td = Storm surge duration (s)
A = Sediment scale parameter (-)
W = Breaker zone width (m)
Ts = Time scale of dynamic profile response (s)
Beta = Ratio of the erosion time scale to the storm duration (-)
Sigma = n/ storm surge duration (rad/s)
R(lt) = R∞ = equilibrium beach response for the peak water level (m)
Y0 = small offset of the shoreline between the sloping beach face and the imaginary or virtual origin of the equilibrium profile (m)
V(lt) = volume of sand eroded between the initial and final profiles per unit length of beach (m³/m)
R(t)/R(lt) = Rate between R(t) and R(lt) (-)
R(t) = profile response (m)

The rate between R(t) and R(lt) (R(t)/ R∞) of the calculations is plotted in the next figure.

![Image](image-url)
Calculations with waves from the Global waves Statistics

The input parameters and the outcomes of the calculations are tabulated in the same table.

### West

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<td>W</td>
</tr>
<tr>
<td>D</td>
<td>Ts</td>
</tr>
<tr>
<td>B</td>
<td>Betha</td>
</tr>
<tr>
<td>Mo</td>
<td>sigma</td>
</tr>
<tr>
<td>g</td>
<td>R (lt)</td>
</tr>
<tr>
<td>Smax</td>
<td>Yo</td>
</tr>
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<td>Td</td>
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<td></td>
<td>R(t)/ R(t) max</td>
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<td>R(t)</td>
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Table 15-2 West

### North West

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<td>HB</td>
<td>W</td>
</tr>
<tr>
<td>D</td>
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</tr>
<tr>
<td>g</td>
<td>R (lt)</td>
</tr>
<tr>
<td>Smax</td>
<td>Yo</td>
</tr>
<tr>
<td>Td</td>
<td>V (lt)</td>
</tr>
<tr>
<td></td>
<td>R(t)/ R(t) max</td>
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<tr>
<td></td>
<td>R(t)</td>
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Table 15-3 North West
### North

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<tr>
<td>Mo</td>
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<tr>
<td>g</td>
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<td>Td</td>
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</table>

Table 15-4 North

### North East

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<td>Mo</td>
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<tr>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 15-5 North East
16 Appendix: Determination of wave height for design hard solutions

The waves a breakwater has to be able to withstand should have a return period that is the same as the lifespan of the structure. Because the lifespan of a hard construction has to be 50 years the wave height was determined of the wave with the same return period. When looking at the data from all sources the following wave heights for a return period of 50 years are found:

<table>
<thead>
<tr>
<th>Return period = 50 year</th>
<th>GWS(^1)</th>
<th>INSMET</th>
<th>Inst of Oceanography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave height (m)</td>
<td>5,80</td>
<td>10,34</td>
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<tr>
<td>Wave Period (s)</td>
<td>8,60</td>
<td>11,04</td>
<td>7,70</td>
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</tbody>
</table>

There is some difference between the results given. The data of the INSMET and the Department of Oceanology are both for the area of Havana. The data of the GWS are for the whole gulf of Mexico and its surroundings. Because of the high values found by INSMET they are not taken into account here. To come to one wave height which can be used to design hard solutions on a mean wave is determined from the data of GWS and the Institute of Oceanology.

The wave has therefore the following characteristics:
\( H_s = 5,24 \text{ m and } T = 8,15 \text{ s.} \)

\(^1\) Havana City Seawall Malecon report 2003
17 Appendix: Lengthening of the breakwaters of the Paso Malo

If the breakwaters of the Paso Malo have an influence on the sediment transport far to the east, stopping the sediment by-pass would be a solution to prevent erosion at Historic Varadero. In UNIBEST a run was done to see if the Paso Malo breakwaters actually have any influence so far eastwards.

A run was done for 50 years with a breakwater of length 500 meter into the sea because the dynamic border is at 485 m of the coast at that point (Section 1). In this way the total sediment capacity is captured by the breakwaters. The results are compared with the results if the breakwaters remain at their normal length of 85 m.

The results are given for both runs:

<table>
<thead>
<tr>
<th></th>
<th>Calle 20</th>
<th>Calle 23</th>
<th>Calle 30</th>
<th>Calle 37</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakwater = 85 m</td>
<td>11.30</td>
<td>-37.10</td>
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<tr>
<td>Breakwater = 500 m</td>
<td>11.60</td>
<td>-37.10</td>
<td>-72.60</td>
<td>-7.70</td>
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</tbody>
</table>

Table 17-1: Change of coastline (m)

The results show that there is a really small influence after 50 years: near Calle 20 there is slightly more accretion then with the normal breakwater length of 85 m.

This solution would require a very large construction (lengthen the existing breakwater with 400 m) and would have a negligible effect on the area considered.
18 Appendix: Multi Criteria Analysis

(explanation of the table 9-1)

In the first table, the meaning of the words used in the table is given and the range of scores.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Variable</th>
<th>Meaning and Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality</td>
<td>Stabilization</td>
<td>The coast line had to be stabilised: it may vary along the year, but further retraction is not allowed as structures will be lost. This is one of the main goals.</td>
</tr>
<tr>
<td></td>
<td>coast line</td>
<td>Range: little stabilised – fully stabilised</td>
</tr>
<tr>
<td>Width beach</td>
<td></td>
<td>The beach width has to be extended with at least 15 meters for safety and recreation. This also is one of the main goals.</td>
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<tr>
<td></td>
<td></td>
<td>Range: little width – large width</td>
</tr>
<tr>
<td>Reliability</td>
<td>How certain is it that the proposed solution works?</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range: uncertain – certain</td>
</tr>
<tr>
<td>Maintenance</td>
<td>How much maintenance does the proposed solution need?</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range: no maintenance – a lot of maintenance</td>
</tr>
<tr>
<td>Environment</td>
<td>Durability</td>
<td>What is from an environmental point of view the durability of the proposed solution?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range: not durable – very durable</td>
</tr>
<tr>
<td></td>
<td>Physical fit</td>
<td>Does the proposed solution physically fit?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range: does not fit – fits very good</td>
</tr>
<tr>
<td></td>
<td>Esthetics</td>
<td>Is the proposed solution esthetical good?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range: not good – very good</td>
</tr>
</tbody>
</table>
## 19 Appendix: Figures of Chapter 10

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<tr>
<th>Muestra</th>
<th>Rango de Tamices</th>
<th>Md</th>
<th>Desv. Stand. (σ)</th>
<th>So</th>
<th>Clasificación</th>
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<td>0.25-0.10</td>
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<td>9.50</td>
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<td>46.60</td>
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<td>30.10</td>
<td>52.70</td>
</tr>
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<td>39.90</td>
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*Table 19-1 Grain characteristics Borrow Zone*
Figure 19-1 Angle Coast rotation critical zone

Figure 19-2 Figure 2 Adjusted SPM fill factor
## MAINTENANCE NOURISHMENT

<table>
<thead>
<tr>
<th>Primary Costs</th>
<th>PRECONX Code</th>
<th>Price US Dollar/Unit</th>
<th>Quantity</th>
<th>Subtotal</th>
<th>Total</th>
</tr>
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<td>C1 Direct Costs of land (m³)</td>
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<td>10500</td>
<td>$46,009.62</td>
<td>$46,009.62</td>
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<tr>
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<td>Design (hours)</td>
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<td>Water and food (per person per day)</td>
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<td>$840.00</td>
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<td></td>
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<td>C3 Direct costs of equipment</td>
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<td></td>
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<td>Dredging vessel (hours)</td>
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<td>$46.75</td>
<td>336</td>
<td>$15,707.87</td>
<td></td>
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<tr>
<td>Throah (hours)</td>
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<td>$5.59</td>
<td>336</td>
<td>$1,877.56</td>
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<tr>
<td>Bulldozer (hours)</td>
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<td></td>
<td></td>
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<td>Wheel loader (hours)</td>
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<td>$1.32</td>
<td>336</td>
<td>$443.91</td>
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<td>Backhoe crane (hours)</td>
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<td>Boating position (hours)</td>
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<td>C4 Direct costs of men of support and small material</td>
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<td>C6 Indirect costs</td>
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<td>C7 Total costs</td>
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<td>C8 Project (20% of the Elaboration costs**)</td>
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<td>$63,748.48</td>
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<td>C9 Total primary costs</td>
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### Secondary Costs

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<th>Secondary Costs</th>
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<th>Price US Dollar/Unit</th>
<th>Quantity</th>
<th>Subtotal</th>
<th>Total</th>
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<tbody>
<tr>
<td>P1 Temporary facilities</td>
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<td></td>
<td></td>
<td>$3,000.00</td>
<td>$3,000.00</td>
</tr>
<tr>
<td>Toilets, material warehouses etc</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>P2 Transport</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracks (hours)</td>
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<td>$8.75</td>
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<tr>
<td>Movable crane 10-20 ton (hour)</td>
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<td>$6.07</td>
<td>336</td>
<td>$2,039.52</td>
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<tr>
<td>P3 Other additional costs</td>
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<td>$2,543.62</td>
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<tr>
<td>Removal unused materials at completion of work (5% of P2)</td>
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<td>$127.18</td>
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<td>P4 Banking</td>
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<td>Risk by making a cost estimation</td>
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<tr>
<td>Risk by making an estimation for the time needed for the project</td>
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<td>Risk of price changes during the project</td>
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<td>P5 Insurance</td>
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<td>P6 Unpredictable costs</td>
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<td>P7 Final secondary costs</td>
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</table>

**Elaboration costs**

- Rate of exchange October 2003: 1 U.S. dollar = 30 Cadiz Pesos
- Cost of construction fluctuates with exchange rate

---

Project group CF015

60
22 Appendix: Wave climate behind the breakwater

In this appendix is the wave climate behind the breakwater described for UNIBEST.

<table>
<thead>
<tr>
<th>West</th>
<th>Hs0</th>
<th>T</th>
<th>H(500m) W</th>
<th>Transmitted wave angle</th>
<th>Ht</th>
<th>Occurrence (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>4.34</td>
<td>0.4</td>
<td>44.2</td>
<td>0.4</td>
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<tr>
<td>60</td>
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<td>44.2</td>
<td>0.96</td>
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<td>1.19</td>
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Figure 22-1 Waves from Western direction

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<th>North West</th>
<th>Hs0</th>
<th>T</th>
<th>H(500m) NW</th>
<th>Transmitted wave angle</th>
<th>Ht</th>
<th>Occurrence (days)</th>
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<td>7.0</td>
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<td>1.37</td>
<td>3.19</td>
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<td>9.0</td>
<td>1.37</td>
<td>1.53</td>
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<td>4.5</td>
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<td>10.0</td>
<td>1.37</td>
<td>0.07</td>
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<tr>
<td>5.5</td>
<td>6.17</td>
<td>2</td>
<td>11.0</td>
<td>1.37</td>
<td>0.27</td>
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</tr>
<tr>
<td>6.5</td>
<td>6.00</td>
<td>2</td>
<td>11.4</td>
<td>1.37</td>
<td>0.11</td>
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<tr>
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<td>2</td>
<td>11.4</td>
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</tbody>
</table>

Figure 22-2 Waves from North-Western direction

<table>
<thead>
<tr>
<th>North</th>
<th>Hs0</th>
<th>T</th>
<th>H(500m) N</th>
<th>Transmitted wave angle</th>
<th>Ht</th>
<th>Occurrence (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>0.5</td>
<td>4.78</td>
<td>0.5</td>
<td>-22.2</td>
<td>0.5</td>
<td>12.19</td>
</tr>
<tr>
<td>1.5</td>
<td>5.41</td>
<td>1.4</td>
<td>-14.0</td>
<td>1.09</td>
<td>12.33</td>
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</tr>
<tr>
<td>2.5</td>
<td>5.76</td>
<td>2</td>
<td>-16.0</td>
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<td>6.56</td>
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<td>-18.0</td>
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<td>6.19</td>
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<td>1.15</td>
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<td>0.25</td>
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<td>7.5</td>
<td>6.50</td>
<td>2.2</td>
<td>-22.2</td>
<td>1.37</td>
<td>0.11</td>
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</table>

Figure 22-3 Waves from Northern direction
### Table: Waves from North-Eastern direction

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<thead>
<tr>
<th>North East</th>
<th>Hs0</th>
<th>T</th>
<th>H(500m) NE</th>
<th>Transmitted wave angle</th>
<th>Ht</th>
<th>Occurrence (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-75</td>
<td>1.5</td>
<td>5.28</td>
<td>0.8</td>
<td>-47.8</td>
<td>0.3</td>
<td>24.76</td>
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<tr>
<td></td>
<td>2.5</td>
<td>5.63</td>
<td>1.5</td>
<td>-26.0</td>
<td>1.14</td>
<td>11.15</td>
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<td></td>
<td>3.5</td>
<td>5.87</td>
<td>1.6</td>
<td>-29.0</td>
<td>1.19</td>
<td>3.78</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>6.11</td>
<td>1.8</td>
<td>-32.0</td>
<td>1.28</td>
<td>1.20</td>
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<tr>
<td></td>
<td>5.5</td>
<td>6.00</td>
<td>1.9</td>
<td>-36.0</td>
<td>1.32</td>
<td>0.40</td>
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<td>6.5</td>
<td>6.00</td>
<td>2</td>
<td>-39.0</td>
<td>1.37</td>
<td>0.13</td>
</tr>
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</table>

**Figure 22-4 Waves from North-Eastern direction**
### Costs of construction of 200 m breakwater

#### HARD SOLUTION: 200 m breakwater

<table>
<thead>
<tr>
<th>Primary Costs</th>
<th>PRECONS Code</th>
<th>Price US Dollar/Unit</th>
<th>Quantity</th>
<th>Subtotal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 Direct Costs of material</td>
<td></td>
<td>$200.00</td>
<td>4320</td>
<td>$864,000.00</td>
<td>$864,000.00</td>
</tr>
<tr>
<td>Concrete prefab (m³)</td>
<td></td>
<td>$100.00</td>
<td>1560</td>
<td>$156,000.00</td>
<td>$156,000.00</td>
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<tr>
<td>Rock (m³)</td>
<td></td>
<td>$20.00</td>
<td>150320</td>
<td>$3,006,400.00</td>
<td>$3,006,400.00</td>
</tr>
<tr>
<td>C2 Direct costs of work by hand</td>
<td></td>
<td>$3.00</td>
<td>1600</td>
<td>$4,800.00</td>
<td>$4,800.00</td>
</tr>
<tr>
<td>Design (hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical preparations (hours)</td>
<td></td>
<td>$3.00</td>
<td>1000</td>
<td>$3,000.00</td>
<td>$3,000.00</td>
</tr>
<tr>
<td>Salaries (hours)</td>
<td></td>
<td>$3.00</td>
<td>33600</td>
<td>$100,800.00</td>
<td>$100,800.00</td>
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<tr>
<td>Water and food (per person per day)</td>
<td></td>
<td>$1.00</td>
<td>2800</td>
<td>$2,800.00</td>
<td>$2,800.00</td>
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<tr>
<td>C3 Direct costs of equipment (including operators)</td>
<td></td>
<td>$50.00</td>
<td>1008</td>
<td>$50,400.00</td>
<td>$50,400.00</td>
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<tr>
<td>Floating crane 20 ton (hours)</td>
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<td></td>
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<tr>
<td>Fuel and lubricants (litres)</td>
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<td>$0.64</td>
<td>200000</td>
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<td>$128,000.00</td>
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<tr>
<td>Insurance for material and equipment</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>C4 Direct costs of means of support and small material (3)</td>
<td></td>
<td>$39,444.00</td>
<td></td>
<td>$39,444.00</td>
<td></td>
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<tr>
<td>C5 Total direct costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1,354,244.00</td>
</tr>
<tr>
<td>C6 Indirect costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$392,730.76</td>
</tr>
<tr>
<td>C7 Total costs</td>
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<td></td>
<td></td>
<td></td>
<td>$1,746,974.76</td>
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<tr>
<td>C8 Profit (20% of the Elaboration costs**)</td>
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<td></td>
<td></td>
<td></td>
<td>$78,340.15</td>
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<tr>
<td>C9 Total primary costs</td>
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<td></td>
<td></td>
<td></td>
<td>$1,825,314.91</td>
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<table>
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<tr>
<th>Secondary Costs</th>
<th>PRECONS Code</th>
<th>Price US Dollar/Unit</th>
<th>Quantity</th>
<th>Subtotal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 Temporary facilities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toilets, material warehouses etc.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P2 Transport</td>
<td></td>
<td>$4.50</td>
<td>8064</td>
<td>$36,288.00</td>
<td>$36,288.00</td>
</tr>
<tr>
<td>Trucks (6 trucks) 5,0 m³</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moveable crane 10-20 ton (hour)</td>
<td></td>
<td>$6.07</td>
<td>1344</td>
<td>$8,158.08</td>
<td>$8,158.08</td>
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<tr>
<td>Supply barge (5 barges) (hour)</td>
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<td>$0.01</td>
<td>2688</td>
<td>$21,504.00</td>
<td>$21,504.00</td>
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<tr>
<td>P3 Other additional costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>removal unused materials at completion of work (5% of P2)</td>
<td></td>
<td>$3,297.50</td>
<td></td>
<td>$3,297.50</td>
<td></td>
</tr>
<tr>
<td>P4 Banking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Risk by making a cost estimation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>by making an estimation for the time needed for the project</td>
<td></td>
<td>$3,297.50</td>
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<td>$3,297.50</td>
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<tr>
<td>Risk of price-changes during the project</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P5 Insurance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P6 Unpredictable costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>P7 Total secondary costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total costs of the construction</td>
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Project group CF015
# Costs of initial nourishment

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<th>INITIAL NOURISHMENT</th>
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<th>Subtotal</th>
<th>Total</th>
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<tr>
<td><strong>Primary Costs</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1 Direct Costs of sand (m³)</td>
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<td>$0.28</td>
<td>400000</td>
<td>$111,538.46</td>
<td>$111,538.46</td>
</tr>
<tr>
<td>C2 Direct costs of personnel</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design (hours)</td>
<td>-</td>
<td>$3.00</td>
<td>1600</td>
<td>$4,800.00</td>
<td></td>
</tr>
<tr>
<td>Technical preparations (hours)</td>
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<td>$3.00</td>
<td>500</td>
<td>$1,500.00</td>
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</tr>
<tr>
<td>Salaries (hours)</td>
<td>-</td>
<td>$3.00</td>
<td>8000</td>
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<tr>
<td>Water and food (per person per day)</td>
<td>-</td>
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<td>1680</td>
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</tr>
<tr>
<td>C3 Direct costs of equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Dredging vessel (hours)</td>
<td>0047158413</td>
<td>$46.75</td>
<td>675</td>
<td>$31,555.99</td>
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<tr>
<td>Thugboat (hours)</td>
<td>0047228425</td>
<td>$5.59</td>
<td>675</td>
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<tr>
<td>Bulldozer (hours)</td>
<td>-</td>
<td>$1.32</td>
<td>675</td>
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<td>Wheeloadeer (hours)</td>
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<td>675</td>
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<td>Backhoe crane (hours)</td>
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<td>0047318451</td>
<td>$4.30</td>
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<td>$3,037.24</td>
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</tr>
<tr>
<td>Booming pontoon</td>
<td>-</td>
<td>$2.50</td>
<td>675</td>
<td>$1,687.50</td>
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</tr>
<tr>
<td>Fuel and lubricants (liters)</td>
<td>-</td>
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<td>160000</td>
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<tr>
<td>Insurance for material and equipment</td>
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<td>-</td>
<td>-</td>
<td>$5,000.00</td>
<td></td>
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<tr>
<td>C4 Direct costs of means of support and small material</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$8,799.02</td>
<td>$8,799.02</td>
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<tr>
<td>C5 Total direct costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>C6 Indirect costs</td>
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<td>-</td>
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<td>-</td>
<td>$87,608.91</td>
</tr>
<tr>
<td>C7 Total costs</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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<tr>
<td>C8 Profit (20% of the Elaboration costs**)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$48,301.49</td>
</tr>
<tr>
<td>C9 Total primary costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$438,010.09</td>
</tr>
<tr>
<td><strong>Secondary Costs</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1 Temporary facilities</td>
<td>-</td>
<td></td>
<td></td>
<td>$3,000.00</td>
<td>$3,000.00</td>
</tr>
<tr>
<td>Toilets, material warehouses etc</td>
<td>-</td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>P2 Transport</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trucks (hours)</td>
<td>-</td>
<td>$0.75</td>
<td>1250</td>
<td>$1,012.50</td>
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</tr>
<tr>
<td>Movable crane 10-20 ton (hour)</td>
<td>-</td>
<td>$6.07</td>
<td>675</td>
<td>$4,097.25</td>
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</tr>
<tr>
<td>P3 Other additional costs</td>
<td>-</td>
<td></td>
<td></td>
<td>$255.49</td>
<td>$255.49</td>
</tr>
<tr>
<td>Naval unused materials at completion of work (5% of P2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$255.49</td>
<td></td>
</tr>
<tr>
<td>P4 Banking</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Risk by making a cost estimation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$50,000.00</td>
<td>$50,000.00</td>
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<tr>
<td>Making an estimation for the time needed for the project</td>
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<td>-</td>
<td>-</td>
<td>$50,000.00</td>
<td>$50,000.00</td>
</tr>
<tr>
<td>Risk of price-changes during the project</td>
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<td>-</td>
<td>-</td>
<td>$25,000.00</td>
<td>$25,000.00</td>
</tr>
<tr>
<td>P5 Insurance</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$50,000.00</td>
<td>$50,000.00</td>
</tr>
<tr>
<td>P6 Unpredictable costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$50,000.00</td>
<td>$50,000.00</td>
</tr>
<tr>
<td>P7 Total secondary costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$233,365.24</td>
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</tbody>
</table>

T Total costs of the construction $671,378.33
## Costs of maintenance program

### MAINTENANCE NOURISHMENT

#### Primary Costs

<table>
<thead>
<tr>
<th>Description</th>
<th>PRECONS Code</th>
<th>Price US Dollar/Unit</th>
<th>Quantity</th>
<th>Subtotal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 Direct Costs of sand (m3)</td>
<td>4421010001</td>
<td>$0.28</td>
<td>110000</td>
<td>$30,673.08</td>
<td>$30,673.08</td>
</tr>
<tr>
<td>C2 Direct costs of personnel</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design (hours)</td>
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<td>133</td>
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<td>$999.00</td>
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<tr>
<td>Water and food (per person per day)</td>
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<td>560</td>
<td>$560.00</td>
<td></td>
</tr>
<tr>
<td>C3 Direct costs of equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dredging vessel (hours)</td>
<td>0047158413</td>
<td>$46.75</td>
<td>224</td>
<td>$10,471.91</td>
<td></td>
</tr>
<tr>
<td>Thugboat (hours)</td>
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<td>224</td>
<td>$1,251.90</td>
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</tr>
<tr>
<td>Bulldozer (hours)</td>
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<td>$1.32</td>
<td>1000</td>
<td>$1,321.50</td>
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<td>Wheel loader (hours)</td>
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<td>Backhoe crane (hours)</td>
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<td>$181.01</td>
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</tr>
<tr>
<td>Survey boat (hours)</td>
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<td>$4.50</td>
<td>224</td>
<td>$1,007.91</td>
<td></td>
</tr>
<tr>
<td>Booming pontoon (hours)</td>
<td>-</td>
<td>$2.50</td>
<td>224</td>
<td>$560.00</td>
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</tr>
<tr>
<td>Measurement material (hours)</td>
<td>-</td>
<td>$1.00</td>
<td>667</td>
<td>$667.00</td>
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<td>Fuel and lubricants (gallons)</td>
<td>-</td>
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<td>5333</td>
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<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>C4 Direct costs of means of support and small material</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$2,940.63</td>
<td>$2,940.63</td>
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<tr>
<td>C5 Total direct costs</td>
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<td>C6 Indirect costs</td>
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<td>-</td>
<td>-</td>
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<td>C9 Total primary costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>$148,137.58</td>
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#### Secondary Costs

<table>
<thead>
<tr>
<th>Description</th>
<th>PRECONS Code</th>
<th>Price US Dollar/Unit</th>
<th>Quantity</th>
<th>Subtotal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 Temporary facilities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toilets, material warehouses etc</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$3,000.00</td>
<td>$3,000.00</td>
</tr>
<tr>
<td>P2 Transport</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trucks (hour)</td>
<td>-</td>
<td>$0.75</td>
<td>448</td>
<td>$336.00</td>
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<td>Moveable crane 10-20 ton (hour)</td>
<td>-</td>
<td>$6.07</td>
<td>224</td>
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<td>P3 Other additional costs</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>initial unused materials at completion of work (5% of P2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$84.78</td>
<td>$84.78</td>
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<td>P4 Banking</td>
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<tr>
<td>Risk by making a cost estimation</td>
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<td>-</td>
<td>-</td>
<td>$25,000.00</td>
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</tr>
<tr>
<td>making an estimation for the time needed for the project</td>
<td>-</td>
<td>-</td>
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<td>$25,000.00</td>
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<tr>
<td>Risk of price-changes during the project</td>
<td>-</td>
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<td>P5 Insurance</td>
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<tr>
<td>P6 Unpredictable costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$25,000.00</td>
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<tr>
<td>P7 Total secondary costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$71,785.46</td>
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<tr>
<td>I Total costs of the construction</td>
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<td></td>
<td></td>
<td>$262,918.05</td>
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</tbody>
</table>
24 Appendix: Costs estimation

breakwater of 1200 m

The total costs of the 1200 m breakwater with nourishment program consist of:
Construction of 1200 m breakwater at $t = 0$
Initial nourishment
Maintenance nourishment every 5 years after the completion of the initial nourishment
## Costs of construction of 1200 m breakwater

### HARD SOLUTION

#### Primary Costs

<table>
<thead>
<tr>
<th>Description</th>
<th>PRECONS Code</th>
<th>Price US Dollar Unit</th>
<th>Quantity</th>
<th>Subtotal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 Direct Costs of material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete prefab (m3)</td>
<td>-</td>
<td>$200.00</td>
<td>2920</td>
<td>$5,840,000.00</td>
<td>$6,120,000.00</td>
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<td>Rock (m3)</td>
<td>-</td>
<td>$100.00</td>
<td>9360</td>
<td>$936,000.00</td>
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<tr>
<td>C2 Direct costs of work by hand</td>
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<td></td>
<td></td>
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<tr>
<td>Design (hours)</td>
<td>-</td>
<td>$3.00</td>
<td>1600</td>
<td>$4,800.00</td>
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<tr>
<td>Technical preparations (hours)</td>
<td>-</td>
<td>$3.00</td>
<td>1000</td>
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<tr>
<td>Salaries (hours)</td>
<td>-</td>
<td>$3.00</td>
<td>201600</td>
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</tr>
<tr>
<td>Water and food (per person per day)</td>
<td>-</td>
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<td>16800</td>
<td>$16,800.00</td>
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<tr>
<td>C3 Direct costs of equipment (including operators)</td>
<td>-</td>
<td>$50.00</td>
<td>6048</td>
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<tr>
<td>Fuel and lubricants (liters)</td>
<td>-</td>
<td>$0.64</td>
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<tr>
<td>Insurance for material and equipment</td>
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<td>$1,075,400.00</td>
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<tr>
<td>C4 Direct costs of means of support and small material</td>
<td>-</td>
<td></td>
<td></td>
<td>$234,744.00</td>
<td></td>
</tr>
<tr>
<td>C5 Total direct costs</td>
<td>-</td>
<td></td>
<td></td>
<td>$234,744.00</td>
<td></td>
</tr>
<tr>
<td>C6 Indirect costs</td>
<td>-</td>
<td></td>
<td></td>
<td>$8,059,544.00</td>
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</tr>
<tr>
<td>C7 Total costs</td>
<td>-</td>
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<td>$10,337,267.76</td>
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<tr>
<td>C8 Profit (20% of the Elaboration costs**)</td>
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<td></td>
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<tr>
<td>C9 Total primary costs</td>
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#### Secondary Costs

<table>
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<tr>
<th>Description</th>
<th>PRECONS Code</th>
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<th>Quantity</th>
<th>Subtotal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 Temporary facilities</td>
<td></td>
<td></td>
<td>-</td>
<td>$3,000</td>
<td>$3,000</td>
</tr>
<tr>
<td>P2 Transport</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trucks (6 trucks) 6.0 m3</td>
<td>-</td>
<td>$4.50</td>
<td>48284</td>
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<tr>
<td>Moveable crane 10-20 ton (hour)</td>
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<td>$6.07</td>
<td>8064</td>
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<tr>
<td>Supply barges (2 barges) (hour)</td>
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<td>$8.00</td>
<td>16128</td>
<td>$129,024.00</td>
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<tr>
<td>P3 Other additional costs</td>
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<td></td>
<td>$395,700.48</td>
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<tr>
<td>P4 Banking</td>
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<td>Risk by making a cost estimation</td>
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<tr>
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</tr>
<tr>
<td>Risk of price-changes during the project</td>
<td>-</td>
<td></td>
<td></td>
<td>$50,000.00</td>
<td></td>
</tr>
<tr>
<td>P5 Insurance</td>
<td>-</td>
<td></td>
<td></td>
<td>$50,000.00</td>
<td></td>
</tr>
<tr>
<td>P6 Unpredictable costs</td>
<td>-</td>
<td></td>
<td></td>
<td>$50,000.00</td>
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<tr>
<td>P7 Total secondary costs</td>
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<td>$649,485.50</td>
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</table>

**Total costs of the construction**

$11,490,338.32

---

Project group CF015

68
## Costs of initial nourishment

### INITIAL NOURISHMENT

#### Primary Costs

<table>
<thead>
<tr>
<th>PRECONS Code</th>
<th>Price US Dollar/ Unit</th>
<th>Quantity</th>
<th>Subtotal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 Direct Costs of sand (m3)</td>
<td>4421010001</td>
<td>$0.28</td>
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<td>C2 Direct costs of personnel</td>
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<td>1600</td>
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</tr>
<tr>
<td>Design (hours)</td>
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<td>$3.00</td>
<td>500</td>
<td>$1,500.00</td>
</tr>
<tr>
<td>Technical preparations (hours)</td>
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<td>3500</td>
<td>$10,500.00</td>
</tr>
<tr>
<td>Salaries (hours)</td>
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<td>$735.00</td>
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<tr>
<td>Water and food (per person per day)</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C3 Direct costs of equipment</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dredging vessel (hours)</td>
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<td>$46.75</td>
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<td>Thugboat (hours)</td>
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<td>Bulldozer (hours)</td>
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<td>Wheel loader (hours)</td>
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<td>Survey boat (hours)</td>
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<td>Booming pontoons</td>
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<td>Fuel and lubricants (liters)</td>
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<td>7000</td>
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<tr>
<td>Insurance for material and equipment</td>
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<td>$5,000.00</td>
</tr>
<tr>
<td>C4 Direct costs of means of support and small material</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C5 Total direct costs</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>C6 Indirect costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C7 Total costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C8 Profits (20% of the Elaboration costs**)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C9 Total primary costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</table>

#### Secondary Costs

<table>
<thead>
<tr>
<th>PRECONS Code</th>
<th>Price US Dollar/ Unit</th>
<th>Quantity</th>
<th>Subtotal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 Temporary facilities</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$3,000.00</td>
</tr>
<tr>
<td>Toilets, material warehouses etc</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P2 Transport</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Trucks (hours)</td>
<td>-</td>
<td>$0.75</td>
<td>590</td>
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<td>Movable crane 10-20 ton (hour)</td>
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<td>$6.07</td>
<td>295</td>
<td>$1,790.65</td>
</tr>
<tr>
<td>P3 Other additional costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$2,233.15</td>
</tr>
<tr>
<td>Naval unused materials at completion of work (5% of P2)</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P4 Banking</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>Risk by making a cost estimation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$50,000.00</td>
</tr>
<tr>
<td>Risk of price-changes during the project</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$25,000.00</td>
</tr>
<tr>
<td>P5 Insurance</td>
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<tr>
<td>P6 Unpredictable costs</td>
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<td>P7 Total secondary costs</td>
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</table>

Project group CF015
The board considers the solutions given by the project paper fulfill the requirements to be presented at Province Forum of Science and Technique:

Yes  X  No ___

Thus, officially signed by:

[Signatures]

Member  Member  Chairman
General notice to the reader:

In the academic programme for Hydraulic Engineering we have in the 4th year (i.e. in the first year of the Master Programme) the requirement that students should do in a group of four to six persons a so-called "groupwork". It is also called "Master Project". During this groupwork they should make a full design of something. The work should be integral, starting with terms of reference, and ending with the real design. This can be a structure, but also it can be a harbour lay-out, a policy plan design, etc. The total time available for the project is in the order of two months and will provide 10 European Credits. It has to be practical and applied.

It is certainly not an M.Sc. thesis assignment (the thesis work is individual, 6 months and more focussed on research or advanced design work on details). But it is also not an apprenticeship, internship or traineeship where the student has to work together with a group of experienced people. For this groupwork they have to solve the problem on their own (of course with guidance).

This report is the result of such a Master Project. This report has been assessed by staff of TU Delft. It has been provided with a passing mark (i.e. a mark between 6 and 10 on a scale of 10), and consequently considered sufficient for publication.

However, this work has not been fully corrected by TU Delft staff and therefore should be considered as a product made in the framework of education, and not as a consultancy report made by TU Delft.

The opinions presented in this report are neither the opinions of TU Delft, neither of the other sponsoring organisations.

Department of Hydraulic Engineering
Delft University of Technology