Coastline evolution at the south of the Figueira da Foz harbour
Application of a mathematical computational model

João Paulo Vicente Henriques

Technical Resume

Supervisor: Prof. António Alexandre Trigo Teixeira

November of 2007
Abstract

Due to the need to improve the protection of the Figueira da Foz harbour in Portugal from the action of the wave climate the north jetty of the harbour will be extended in 400 m. The thesis that is resumed here assesses the impact of the extension of the north jetty in the stretch of coastline between immediately the south side of the southern jetty and Costa de Lavos groin. The extension of the north jetty will reduce the littoral drift which is assumed as $1 \times 10^6 \text{ m}^3\text{/year}$ in the north-south direction and is nourishing the beaches at the south side of the harbour. This will unbalance the equilibrium of the coastline.

The littoral drift depends on the wave climate nearshore therefore the first step is the propagation of a representative wave climate offshore the Mondego Cape to the nearshore area, using a mathematical computational model, SWAN. With the conditions nearshore it is possible to calculate the gradient in the littoral drift along the stretch of coastline in study using a computational mathematical model, UNIBEST LT. The littoral drift calculations allow the simulation of the evolution of the shoreline using once again a computational mathematical model, UNIBEST CT.

The simulation results show that the most sensible points in terms of erosion are immediately downdrift the jetty harbour and the groin field (direction north-south) and that the groin field and the Costa de Lavos groin will contribute for the control of the erosion. It might be important to observe the evolution and the conditions of the structures, like seawalls, downdrift the jetty and close to the groins.

Key-words:
Shoreline evolution, wave climate, wave propagation, littoral drift.

1 Introduction

The stretch of coastline in study is situated on the southern side of the Figueira da Foz harbour in Portugal. Figueira da Foz is situated at the Portuguese west coast. The stretch of coastline goes from the south jetty of the harbour to Costa de Lavos groin and it has approximately 5800 m length. Figure 1-1 shows the geographical location of the stretch.

Figure 1-1 Geographical location a) Figueira da Foz b) detail view (Source: Google Earth, April 2007)
The wave rays\(^1\) have a predominant northwest direction. The net littoral drift along the coast at the north side of the Mondego Cape is estimated as in the order of \(1 \times 10^6 \) m\(^3\)/year with a north-south direction, eventually between \(1 \times 10^6 \) m\(^3\)/year and \(1.5 \times 10^6 \) m\(^3\)/year according to Barata, Teles and Vieira (1996).

The importance of the stretch in study

In the stretch of coastline in study the most important facts to refer are the presence of the Cova and Costa de Lavos villages both adjacent to the coastline. The existence of those villages is the main reason for the constructions of the groin field and Costa de Lavos groin. The groins protect the villages from the coastline erosion. At the groin field and at the north side of Costa de Lavos groin the beaches are classified as concession areas. In the stretches defined by the groin field and near Costa de Lavos groin there are protected areas for swimmers.

The past of the area in study

Dias, Ferreira and Pereira (1994) refer that as a consequence of the construction of the jetties (between 1961-1966), first the Figueira da Foz beach and second the Buarcos beach started to suffer a process of sediments accretion. Between 1962 and 1980 the Figueira da Foz beach width increased around 440 m and the Buarcos beach width increased 180 m, yielding an accumulation area in the order of \(6 \times 10^5 \) m\(^2\) and a volume in the order of \(11 \times 10^6 \) m\(^3\). In the beginning of the 1980 decade the shoreline was stable. On the opposite side due to the retention of sediments by the northern jetty the beaches in the southern side of the harbour stopped being nourished resulting in a strong erosion process. First the landward movement was felt along the Cova beach and later at the Costa de Lavos and Leirosa coastlines, downdrift the Cova beach. In 1979 a groin field with 5 groins was constructed at Cova coast (950 m to the south of the harbour) to protect this stretch of coast from erosion. The erosion felt at Costa de Lavos was not so large as the erosion felt at the Cova beach. The groin of Costa de Lavos was constructed in 1979 to protect the village.

The present situation

At present the sediments retaining capacity of the beach updrift the northern jetty has reached the limit, meaning that all the sediments that reach the northern jetty by-pass to the southern side establishing a new equilibrium in the beaches downdrift the harbour.

Since the 1990 decade, according to Teixeira (2006) it is usual to perform dredging operations in the mouth of the harbour to control the depth contours to a minimum water depth demanding for the shipping navigation. Besides the dredging performed in the mouth of the harbour it is also common to dredge sand from the submerged north side of the northern jetty, and also but less common sand extraction was performed directly from the emerged sand beach in the adjacent area to the northern jetty. The dredging operations did not have a constant value along the years but the total value of sand removed, dredged plus extraction, can be estimated as around \(400 \,000 \) m\(^3\)/year. If that amount

\(^1\) Wave rays angles are measure from the north, clock-wise.
of sediments is not placed in the beaches downdrift the harbour then the by-pass volumes at the south jetty have a deficit of 400 000 m$^3$/year compared with the littoral drift volume updrift.

Another important information is the existence of a submerged bar running from the estuary mouth parallel to the shore, however, the characteristics of the bar are not known. Observations in situ show that the bar induces the wave breaking.

**Scope**
The goal of the thesis is to assess the impact that the extension of the jetty in 400 m will induce in the shoreline immediately downdrift the harbour.

## 2 Wave propagation

The wave climate influencing the evolution of the coastline has to be known relatively nearshore, close to the edge of the active cross-shore profile. For that the wave climate offshore was to be propagated from offshore to nearshore using a mathematical computational model.

**Past researches, the wave climate offshore**
The wave climate nearshore was obtained by the propagation of a wave climate offshore the Mondego Cape, at 90 m depth. The wave climate used offshore was a representative wave climate represented by 6 waves obtained by Barata, Teles and Vieira (1996).

The wave climate offshore the Mondego Cape coast are the wave height, the wave period, the wave frequency and the directions (the wave direction is the angle between the wave ray and the north, clock-wise). The net littoral drift for the following wave scenario is $1.3 \times 10^6$ m$^3$/year.

In Table 2-1 the waves 1, 2, 3, 4 and 5 are associated with the net longshore transport in the southern direction and wave 6 is representing the net longshore transport in the northern direction.

<table>
<thead>
<tr>
<th>Wave</th>
<th>Height (m)</th>
<th>Period (s)</th>
<th>Direction (°)</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.75</td>
<td>12.0</td>
<td>315</td>
<td>50.00</td>
</tr>
<tr>
<td>2</td>
<td>2.25</td>
<td>12.0</td>
<td>303.75</td>
<td>30.02</td>
</tr>
<tr>
<td>3</td>
<td>3.75</td>
<td>12.0</td>
<td>326.25</td>
<td>9.80</td>
</tr>
<tr>
<td>4</td>
<td>4.75</td>
<td>15.0</td>
<td>315</td>
<td>1.64</td>
</tr>
<tr>
<td>5</td>
<td>6.25</td>
<td>15.0</td>
<td>315</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>3.75</td>
<td>12.0</td>
<td>281.25</td>
<td>7.54</td>
</tr>
</tbody>
</table>

**Wave propagation**
The numerical model used to propagate the wave climate from offshore into nearshore is SWAN. The SWAN numerical model is incorporated in the Delft3D model interface developed by WL Delft Hydraulics, in The Netherlands. Delft3D is an integrated model that comprises several models within the area of Hydraulic Engineering. To propagate the wave climate it is necessary to represent the bottom profile. The bathymetry data was taken from a nautical map of the Instituto Hidrográfico in Portugal. The propagation was run for a water level 2 m above the local Datum. The most important
outputs are the wave height and the wave rays directions. Figure 2-1 shows the wave ray angle approach at the 12 m depth contour.

![Figure 2-1 Wave ray angle approach at 12 m depth contour]

3 Coastline Evolution

To compute the evolution of the coastline the single-line theory is assumed, which means the cross-shore phenomena are neglected and it is only taken into consideration the longshore variation of the shoreline. The evolution of the shoreline depends on the transport gradients alongshore. In the stretch of coastline under study the longshore sediment transport is mainly dependent of the wave climate. By this approach the wave ray angle approach and the wave height are very important to quantify that transport. To calculate the sediment transport alongshore the Van Rijn formula was used. According to the Van Rijn formula the total longshore sediment transport is given by the sum of the bed load transport and the suspended load transport. The formula also makes a distinction between the wave induced transport and the tidal current induced transport. However the effects of the tidal currents were not taken into consideration because the sediment transport in the area is mainly due to the breaking waves. The parameters to input in the Van Rijn formula are: the median grain diameter D_{50}, grain diameter D_{90}, sediment density, current related bottom roughness, wave related bottom roughness, fall velocity suspension material, viscosity, relative bottom transport layer thickness, porosity and a correction factor.

Past researches, the by-pass volumes at the south jetty

According to the littoral drift values mentioned before, as well the dredged volumes, and to the available data from the impact of the construction of the jetties in the decade of 1960, Teixeira (2006) estimated the volume of sediments by-passing the south jetty for the future extension in 400 m of the north jetty. Three by-passing scenarios were assumed. It is expected that in 12 years the by-pass conditions reach a new equilibrium, meaning a by-pass volume in the order of 1x10^3 m$^3$/year 12 years after the extension period.

- **Scenario A:** it is assumed that all the sediments by-passing the north jetty will also by-pass the south jetty, or by natural way or by artificial way;
• **Scenario B**: it is assumed that in the first 5 years after the extension of the jetty the by-passing is identical to the scenario A but between the years 6 and 12 it is assumed that maintenance dredging operations will not put sand in the stretch of coastline and that the dredging volumes are the same as the average in the last years, 400 000 m³/year;

• **Scenario C**: It is admitted that the volumes by-passing the south jetty are in the order of 60% the volumes that by-pass in the scenario A.

These were the by-passing scenarios used to perform the simulations in the thesis.

**Shoreline Modelling**

The shoreline evolution is computed with the UNIBEST CL+ model developed by the *WL Delft Hydraulics*, in The Netherlands. UNIBEST CL+ comprises two models, UNIBEST LT (Longshore Transport) and UNIBEST CL (CoastLine). The first calculates the transport gradient alongshore using as main philosophy the transport rays. The transport rays are the rays perpendicular to the coast that define the characteristics of the longshore transport in the ray, such as the distribution of the sediment transport in the cross-shore profile, the shore equilibrium angle for the specified wave climate, the direction and the magnitude of the sediment transport. The second model, UNIBEST CL, calculates the evolution of the shoreline based in the transport rays gradient calculated with UNIBEST LT.

The shore angle was simplified so that it reproduces better the reality since the sediment transport calculation is very sensitive to the angle between the wave rays and the coastline rays. The closure depth is 14 m. The parameters of the Van Rijn formula were calibrated adjusting the parameters values so that when using the Van Rijn formula in a beach cross-shore profile in the area of Aveiro we get values for the littoral drift in the order of 1x10⁶ m³/year. For the cross-shore profile the littoral drift was calculated considering two cross-shore profiles: the first with the representation of the submerged bar typical from that area and the second without the representation of that submerged bar. The coast angles used were 284º and 285º, typical from the area. By this approach the parameters that give for the Aveiro coast a net littoral drift in the order of 1x10⁶ m³/year are:

- Mean grain size between 400 and 450 μm and D₉₀ = 650 μm;
- Sediment fall velocity = 0.059 m/s;
- Current related bottom roughness = 0.05 m;
- Wave related bottom roughness = 0.06 m;
- Relative layer thickness = 0.03;
- Porosity = 0.4;
- Viscosity = 1.2x10⁻⁶ m²/s (considering 14°C for the water temperature).

The results also show that a difference of 1º in the coast angle can imply a deviation of the littoral drift in the order of 10% and that the presence of the bar may induce a variation up to 300 000 m³/year. These facts are important because in the stretch under study it is not considerer the presence of the submerged bar in the cross-shore profile for the computation, as well because of the large angle gradient that the stretch of coast presents (from around 265º till 290º, approximadetely).

The computed littoral drift along the stretch is represented in Figure 3-1.
As can be seen in Figure 3-1 the net littoral drift decreases from the groin field to Costa de Lavos groin and the order of magnitude of the transport is smaller than the expected along the stretch. The calculated net littoral drift gradient does not correspond to the physical reality observed in the stretch. Observations in situ show that the stretch is in relative dynamic equilibrium and that the shoreline movement in the last years is not significant. Figure 3-2 may explain the gradient along the stretch because it shows the angle deviation between the bathymetry at the 12 m depth contour and the wave ray angle approach.

Since the sediment transport is highly dependent on the angle between the bathymetry and the wave angle the computed results are understandable. Thereafter the UNIBEST CL model was calibrated to reproduce the physical reality observed, meaning that the volume of sediments entering the system should be in the same order of the volume of sediments going out of the system.

The simulations were performed for 9 scenarios and for a period of simulation till the end of the year 12 after the period of extension. The scenarios A1, B1 and C1 correspond to a shoreline evolution period of 14 years (2 years for the extension period + 12 for the shoreline of Figueira da Foz beach reaches a new equilibrium) the by pass-function are the same as for the scenarios A, B and C of the previous study (Teixeira (2006)). These scenarios take into consideration the existence of the seawall immediately downdrift the south harbour jetty. The scenarios A2, B2 and C2 are similar to the scenarios A1, B1 and C1 but do not consider the seawall existence. Finally the scenarios A3, B3 and C3 correspond to a shoreline evolution of 12 years, which means the extension period is not taken into account. The seawall is considered.
The shoreline evolution was simulated for a mean sea level of 2 m above the local Datum. The wave conditions did not consider the diffraction induced by the extension of the north jetty and the distribution of the sediments by-passing the south jetty was simulated by the input of sources along the stretch between the south jetty and the first groin of the groin field, counting from the north. It was also considered that the littoral drift immediately downdrift the south jetty is null and that increases linearly to the first groin of the groin field (counting from the north). Near the groins and south jetty the cross-shore phenomena were not simulated, such as rip currents. The effective groin length was not considerer (it was used the full length) which may overestimate the accumulation near the groins, on the updrift side. The existence of the submerged bar was not considered in the cross-shore profile.

Results
The simulations show that for all the scenarios immediately downdrift the groin field and the jetty harbour the shoreline will have a landward movement. The groin field and Costa de Lavos groin contribute for the control of the erosion. The maximum landward movement of the shoreline is 115 and 110 m immediately downdrift the groin field for the scenarios A1 and A3. For the scenarios B1 and B3 that value is 160 and 155 m and for the scenarios C1 and C3 is 160 and 150 m, respectively. Immediately downdrift the jetty the landward movement is smaller but the precise values should be considerer with great care because of the way the sources of sediments were input in the model. However it should be mentioned that in all the scenarios the seawall was reached by the erosion. The results show that the scenarios A2, B2 and C2 are not so different from the scenarios A1, B1 and C1, except immediately downdrift the south jetty where the scenarios A2, B2 and C2 have larger landward movements due to the inexistence of the seawall in the model. The scenarios A3, B3 and C3 show some differences with the scenarios A1, B1 and C1. The main differences are in the erosion rates. The landward movement is larger for the scenarios A1, B1 and C1 (14 years of simulation) than for the scenarios A3, B3 and C3 (12 years of simulation) but the erosion rates are smaller in the first scenarios because the by-pass function is smoother in the first 2 years for the first cases of simulation (the first 2 years correspond to the extension period). The recuperation of the stretch will be very slow for all the scenarios. For the scenario A1 it starts at the beginning of the year 7 after the extension period and for the scenarios B1 and C1 it may take more than 10 years after the extension period. Figures from Figure 3-3 to Figure 3-7 show the shoreline evolution for the scenario A1.
Figure 3-4 SCENARIO A1 - Shoreline evolution at the end of the year 3 after the extension period

Figure 3-5 SCENARIO A1 - Shoreline evolution at the end of the year 6 after the extension period

Figure 3-6 SCENARIO A1 - Shoreline evolution at the end of the year 9 after the extension period

Figure 3-7 SCENARIO A1 - Shoreline evolution at the end of the year 12 after the extension period
Figure 3-8 and Figure 3-9 show the shoreline evolution for the scenario B1 and C1 respectively.

The results obtained by these simulations show larger landward movements immediately downdrift the groin field but smaller landward movements immediately downdrift the jetty than the simulations performed by Teixeira (2006). This fact indicates the strong correlation between the results and the calibration procedure, for example the way the sources are input in the model and the way the littoral drift was assumed in the stretch between the south jetty and the groin field.

4 Conclusions

The final conclusions taken from this study can be divided in two parts. The first, general conclusions about the dynamics of the Portuguese west coast and the second about the stretch of coastline under study.

General conclusions about the Portuguese west coast in the neighbourhood of the stretch in study may indicate that the cross-shore profile of the coast may be characterized by a decreasing of the mean grain size from the foreshore into the seaward direction. The results show mean grain sizes in the order of 400 μm and 450 μm to compute the values of the littoral drift assumed for the coast; The presence of the submerged bar may have an important role in the volume of sediments transported alongshore because the computational results show a variation up to 300 000 m³/year; Finally the...
variation of 1° in the shore angle may induce a significant gradient in the littoral drift because the computational results show a gradient around 10% of the littoral drift. For a littoral drift in the order of $1 \times 10^6 \text{ m}^3/\text{year}$ it can imply a deviation up to 100 000 m$^3$/year.

The general conclusions about the study of the stretch of coastline downdrift the south of the Figueira da Foz harbour are:

In the present the stretch seems to be in relative dynamic equilibrium; The high curvature of this stretch implies a large gradient (the stretch is very sensitive to the wave angle approach) in the computational modelling of the littoral drift, and do not correspond to the real observations of the stretch; The extension of the jetty may induce a similar behaviour in the coastline dynamics than the behaviour described when the jetties were constructed in the decade of 1960; The stretch downdrift the Figueira da Foz harbour should fell signs of erosion due to the smaller sediment volumes by-passing the south jetty; The volumes of sediments accumulated in the mouth of the estuary have an important role in the stretch downdrift dynamics.

More particular conclusions about the modelling of the coastline evolution are that the critical points of erosion are immediately downdrift the south jetty of the harbour and immediately downdrift the groin field; It might be important to observe the evolution of the coastline, at least at the critical points; The modelling for a period of 14 years (2 of construction +12) gives larger values of erosion at the critical points than the modelling for a period of 12 years, although it takes more years of simulation to reach the maximum erosion values because of the smoother rate of decreasing volumes by-passing; The groin field and the Costa de Lavos groin may have an important role controlling the erosion but it is recommended to observe the evolution in this stretches due to the fact that they are concession areas, swimmers areas and because of the proximity of the villages.

The erosion rates have a strong correlation with the way the volumes by-passing the south jetty distributes in time. This was shown by the comparison between the scenario B1 and C1 (as well between A1 and A3, B1 and B3 and C1 and C3) where the final position of the shoreline is very similar but the evolution along the years is different.

The recuperation of the stretch will be very slow and it may take more than 10 years eventually; The dredged volumes in the estuary mouth should be, if compatible, placed in the active profile of the beaches downdrift because those volumes correspond to the littoral drift deficit that unbalances the system. The placement of the sediments may help in the recuperation of the stretch.

References