Hydro-morphological study
Douro Estuary

Part 5
Morphological evaluation

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PORT AND WATERWAY ENGINEERS
1. INTRODUCTION

The Administracao dos Portos do Douro is confronted with the fact that future expansion of the port areas of Leixoes is limited by the surrounding hills and urbanisation. One of the alternatives for future expansion might be the creation of port facilities in the Douro estuary, where a relatively large, flat area is available.

However, the river entrance is rather unstable from a morphological point of view, so that regular dredging is required to maintain an access channel.

In order to eliminate the risk of unexpected morphological changes in the Douro estuary, due to harbour works APDL has decided to study the morphological aspects of the Douro bar thoroughly, and to make a design for a mathematical model to investigate the influence of harbour works in the area.

This study was offered to APDL by the Sociedade Portuguesa de Dragagens in January 1982. After receipt of the letter of adjudication from APDL, dated July 29th, 1982, Hydronamic bv was asked by S.P.D. to start the study.

The study is divided into six phases, viz:

a1. wave penetration calculation
a2. calculation of longshore transport
a3. calculation of the tidal prism
b. morphological evaluation
c. set-up of the mathematical model

As described in our proposal of January 1982, a report for each phase will be presented to APDL.

This report gives the morphological evaluation of the mouth of the river Douro. The evaluation is based on the findings during the measurement campaign (8/11/82 - 26/11/82), on the results of phase α1 - α3 and on the data from the historical charts of the Douro mouth (1872 - 1972).
2. CHARACTERISTICS OF THE RIVER DOURO

The river Douro (see fig. 1) flows from Urbion mountains in Spain 752 kilometers to its mouth at Porto. The total height difference between the source of the Douro and the sea is 2060 m, resulting in an average slope of $2.73 \times 10^{-3}$, which is relatively steep. The river basin is 94,500 km². The main type of rock in the river basin is granite. Due to this fact, the river scours deep gorges, not wide valleys. The natural runoff of the river Douro is completely determined by rainfall, because snow occurs only in small quantities in the higher regions. Because the bottom consists of hard rock, the runoff reacts rather quickly to rainfall. This is caused by the fact that the storage capacity of the soil over the granite rocks is small. This rainfall in the basin causes an almost immediate increase in river discharge.

However, in the Douro basin a number of dams have been built. These have been built for the production of electricity, although they could also improve the navigability of the river and be used for irrigation purposes. Dam construction in the river Douro has been favoured by the impermeability of the granite rocks of the Douro basin.

Although the last dam (at Crestuma) is still under construction, the dams have completely changed the hydrology of the river. The main purpose of the dams is the production of electricity. In order to do this to optimum, the user (E.D.P.) tries to keep the lakes behind the dams as full as possible. This means that the river discharge
is governed by the electricity demand, for the period in which the reservoirs are not completely full. When the dams are full, the natural discharge will also be the effective discharge. The discharge in excess of the electricity demand will be sluiced through the dams. This effect is shown in fig. 2a and 2b. (It has been assumed that the electricity demand has a constant value). The total discharge during one year is nearly identical for both situations i.e. with and without dams. (The total discharge in the situation with dams is slightly less because of increased evaporation in the reservoirs).

The sediment discharge of a river is function of the current velocity in the river. The relation is highly unlinear, in fact \( S = f(v^\alpha) \) in which the power \( \alpha \) has a value between 3 and 5. For coarse material, as transported by the Douro, there is also a threshold value. That means that if the velocity is below a certain value, the sediment transport is zero. In fig. 2c and 2d the sediment transport is shown for the river regimes of fig. 2a and 2b. It is quite clear that the transport in the case of a river with dams is much less than that of an untamed river. This phenomenon has been quite important for the morphology of the river Douro during its recent past and will be so in future.
3. THE INFLUENCE OF CURRENTS

General

At the entrance of the river Douro two major types of currents can be distinguished:

a. currents caused by tidal influence
b. currents caused by river discharge

During and shortly after dry periods in the catchment area of the Douro, the discharge has a very low, constant value. Only after longer periods of rainfall are there peak discharges. This is due to the fact that only then do the dams in the river start to sluice superfluous water. When there is no increased river discharge, the currents are almost completely influenced by tides; the entrance acts as a well mixed tidal inlet, with small tributary inflow. During periods of high river discharge, the fresh water influx has a great influence. The currents are clearly not mixed and a salt wedge can be observed.

In the next two paragraphs the situations will be described with tidal currents only and with a combination of tidal currents and fresh water discharge. It must be noted that the second situation is based on theory and measurements, but that the first one is based mainly on theory, because until now no measurements have been performed during periods of low runoff.
hindered by the Fogamanadas, and does not attack the Cabedelo near point A. Near B and C there is a heavy attack by the current. This attack causes an erosion of the submerged slope of the Cabedelo, (mainly the part below zero sealevel). The eroded sediment is transported inside. Directly east of the Cabedelo, the current has space to expand and current velocity decreases. Sedimentation starts.

Because only the flow-lane which passed over the submerged slope of the Cabedelo transports sediment, sedimentation occurs only in this flow-lane. The current in the other flow-lanes does not contain sediment, because it was unable to pick up sediment (due to the rock bottom).

Consequently sedimentation may be expected in area D only.

This process continues until the water levels inside and outside Cantareira are approx. the same. Then the current stops.

In the mean time, the water-level at sea is already falling. The same process now occurs in the opposite direction. However, there are small, but important differences, in comparison with the flood situation. The incoming flow is less concentrated than the outgoing flow, but the concentration of flow is now at the other side of the Cabedelo (see fig. 4).

At the start of the ebbing tide, the water-level is high so that the Pedras do Lima are flooded. Water therefore flows from the S. Paio area along the head of the Cabedelo into the main flow channel. The deposits of the flood tide are removed. Also at C, the underwater slope erodes. In the main channel there is no erosion, because the bottom consists of material that cannot be eroded.
West of the end of the Cabedelo, due to the Fogamanadas, the current decreases in velocity, an eddy is even formed. The decrease in velocity, also caused a decrease in sediment transport capacity, and consequently sedimentation. Because of the shape of the current pattern, a part of the sediment does not settle at E, but is transported by the current into the sea more to the west. There is an expansion and a decrease in velocity. Thus, the rest of the sediment settles near F. This process continues until the water-levels inside and outside Cantareira are approx. the same. Then the current stops.

In the mean time, the water-level at sea is already rising. Because of inertia, the flow continues somewhat after the moment of equal water-levels, so that directly after the moment of low water, the sea tries to penetrate for the estuary, but the continuing ebb current prevents this for a short time, on the west side. On the south side, at the Fogamanadas, the sea can enter perpendicular to the main current. At this moment, some sand can be transported through the Fogamanadas.

Usually, tidal inlets form at this location a so-called flood channel. At the existing Douro entrance, such a flood channel cannot be formed because of the hard rock of the Fogamanadas. In theory, a flood channel should also be formed at the north side of the entrance. This channel can be found just west of the Felgueiras lighthouse. However, this channel cannot accurately be described as a flood channel, because a great part of the ebb current also passes through it.
This due to the topography of the river entrance, with the Felgueiras lighthouse as a fixed point on hard rock.

Summarising, one may conclude that during flood tide the head of the Cabedelo is eroded and that the sediment settles near D. During ebb tide, erosion occurs at D at the head of the Cabedelo and that sedimentation takes place near E and F. The sedimentation near E will be removed during the first hours of flood tide. Consequently, due to tidal action, the gap between Cantereira and the Cabedelo will become wider, the slope of the head of the Cabedelo will become steeper and the area near F will become shallower.

Tidal currents combined with river discharge

After relatively long periods of rainfall, the reservoirs in the Douro are full, and river authorities start to sluice water. In this situation, the current pattern at the river entrance is considerably influenced by the freshwater discharge of the river. An important aspect in the interaction between the sea and the river is the difference in salinity. Seawater is heavier than river water because of the higher salinity of seawater.

The starting point is again low water, with the assumption that the velocity of the water is zero (this is incorrect, as will be demonstrated later). At sea the water level is rising, and the water tries to penetrate the estuary. However, the river is also discharging water, which tries to flow into the sea. In fact water is supplied from two sides at the same moment. Thus, on average there will be no flow at all, only rising water. See also fig. 5a and 5b for a schematic explanation.
Because of the differences in weight, the pressure near the bottom in the salt water is higher than in the fresh water. At the bottom, the seawater is able to penetrate the fresh water. Because the average velocity in the profile has to be zero, at the surface the fresh water starts to flow in the direction of the sea (see fig. 5c).

Of course this situation only occurs if the river discharge is causing a rise in the water level which is identical to the rise of the sea. This does not occur for two reasons. Firstly the river discharge seldom provides exactly the required quantity of water, and secondly the river discharge is relatively constant during a tide, which causes a linear rise of the water level, while the rise of the sea is sinusoidal. See fig. 6a. The (improbable) case that the river provides the correct quantity of water means that during the phase of the rising tide the influence of the river is greater, (thus a net outgoing current) and that during the second phase the influence of the sea is greater (thus a net incoming current). In reality, the situation is more as indicated in fig. 6b for lower discharges and in fig. 6c for higher discharges.

Due to this process, a relatively small quantity of seawater will flow into the estuary. This means that the transport of sediment into the estuary is also relatively small. Measurements indicated that the velocity near the bottom is very low. The transport capacity of the penetrating salt water is therefore also very low.

This process continues until high water. After high water, the water level at sea is falling, the river discharge, however, continues.
Consequently the water level inside the estuary is not falling as fast as it did during times of low freshwater discharge. Because the difference in water level inside and outside is larger, the velocities in the gap between Cantareira and the Cabedelo are also much higher than in the case of tidal influence only.

As stated before, the sediment transport capacity of water depends on a high power of the velocity. An increased velocity implies a greatly increased sediment transport capacity, and thus much more erosion.

The bottom is not able to erode, but the slope of the Cabedelo can be eroded and will be eroded. The effect of this erosion can be observed clearly during low water. The inner slope of the head of the Cabedelo is much steeper than the outer slope. Fig. 7 gives a view of this slope. The effects of erosion can be seen clearly. The picture was made during low water. The sketched profile shows that the current erodes the slope between mean water level and a meter below low water. The higher section of the slope is not affected because during the time that the water is high enough to erode this section, the velocity is not yet great enough.

The sand eroded here is transported towards the sea, also to area E and F. Because the velocity of the ebb current is now greater than in the situation with tide only, sediment is transported further into the sea.

The velocity is high and the quantity is big. The inertia of the system has thus a big influence. This means that after the moment of low water the flow will also continue. However, at the bottom, the seawater starts to penetrate the estuary. This penetration
occurs mainly through the Fogamanadas. The velocity of this salt water is however, rather low, so not very much sediment is transported.

Besides the circulation of coastal sands, as described above, there is also a sediment load of the river itself. Due to its character, the sediments of the river consists mainly of coarse sand. The quantity of the transported sediment is quite low, because much sediment is caught in the reservoirs and also because the river is deeper than the equilibrium depth. This last phenomenon is caused by the dredging of a channel in order to make the Douro navigable, and also by deep pits, dredged by excavation contractors. These pits especially act as sandtraps, so almost no sand can reach the river section west of Freixo.

If, during extreme runoff, the river transports any sediment, this sediment is transported through the main channel and settles at the west of area F. (It settles there, because the velocity is very high).

Summarising, one may conclude that during flood tide nearly nothing happens, but that during ebb tide the head of the Cabedelo is eroded and that the sediment settles in areas E and F. The siltation in area F will create a shallow offshore bar. The siltation in area E will cause an outgrowth at the head of the Cabedelo in a westerly direction.
Fine particles, if any, do not influence the morphology of the area. During high river runoff they are transported far out to sea.

A mud zone can be found approx. 3 km west of the coastline. Sedimentation of this fine material may also occur in the S. Paio area, where the water is very quiet. In due course, this area will completely silt up. In the S. Paio area there is almost no current. This is caused by the Pedras do Lima. Since the construction of this mole the S. Paio area is silting up very gradually. The fact that the siltation is very low can be seen comparing the nautical charts of 1872 and 1972.

During very extreme runoff of the river, the head of the Cabedelo may be washed away completely. The erosion of the Cabedelo in southward direction is, however, always stopped by the Pedras do Lima. Erosion of the southern section of the Cabedelo (thus the creation of a new river mouth) can only occur if the water level inside rises higher than the top of the Cabedelo. Especially after construction of the last dams in the river Douro, is this thought to be extremely unlikely. (It would probably occur if the dam at Crestuma failed).
5. THE INFLUENCE OF WAVES

Waves come from W-NW directions, and are influenced by refraction, as calculated in detail in volume 1 of this report. One of the major facts from the refraction analysis is that in the area between the Fogamanadas and the Avenida Dom Carlos I the waves are very low, even during considerable high waves off the coast. During the measuring campaign in November, this was confirmed by visual observation (see vol. 4). High, waves with long period generally broke on the shallow bank in area F see fig. 8. There they stirred up large quantities of sand. Although it was impossible to measure in this area during periods of high wave action, one could see from the shore that the white caps of the breakers were coloured brown by the sand which was stirred up.

Due to this wave breaking, sand is transported by a longshore current along this shallow bank towards the south. The longshore current is driven by the shear-stress component of the radiation stress. Radiation stress is a type of stress, which occurs in water due to the decrease of wave height.

Besides the transport by longshore current towards the south, some sediment is also transported by waves directly towards the coast. This transport occurs especially in long waves.

Normally a wave is unable to transport sediment, because there is no net velocity in a wave. (In a wave, the water particles remain on the average in the same place). But when long waves are penetrating a shallow area, they can transform into a special type of wave, viz.
a singular wave. In this wave there is an average velocity, and this velocity can transport the sediment, stirred up by general wave action. Measurements executed 400 m west of the Cabedelo confirm this.

From the above, it follows that offshore wave action transports the sediment from area F directly to the Cabedelo by mass transport in singular waves, or towards the trunk of the Cabedelo by longshore current. A small part of the sediment arrives at the coast south of Seca do Bacalhao. This sand is transported southwards to supply the beaches. (See also the chapter on coastal erosion around Porto). Most of the sand reaches the coast north of Seca do Bacalhao. This sand supplies the Cabedelo.

Along the Cabedelo, the incoming direction of the waves is also W-NW. In general, such an incoming wave direction would cause a sediment transport in southward direction. However, due to wave set up, there is an additional force towards the north, which exceeds the southward force due to the breaking waves.

Wave set up is a phenomenon, also related to radiation stress. Due to wave breaking, the average wave height at a coast will rise. The rise is a compensation for the stress-component in the direction of the coast. When no breaking waves occur, there is of course no wave set up. In the area north of the Fogamanadas there are no breaking waves. The set up there is zero. Along the Cabedelo heavy wave breaking occurs, and there is a considerable set up. The water level south of the Fogamanadas is consequently higher than north of them, and this implies a current from south to north.
Because of the heavy wave breaking south of the Fogamanadas, a lot of sediment is brought into suspension, and it is quite easy for the set up induced current to transport a lot of sand along the Cabedelo towards an area north of the Fogamanada.

With the present shape of the Cabedelo, the small waves, which still reach the head of the Cabedelo (especially during high water) may transport the sediment to the inner side of the Cabedelo.

During the measuring campaign in November, this could be observed clearly. When the wave height increased, the sand-cliffs of fig. 7 complete disappeared and were transformed into a gentle beach.

When the head of the Cabedelo was turned in a seaward direction (which was in the past the more usual configuration), the sediment was transported towards the south side of the head by the set up current. At the west side, the waves would erode the head, and transport the sediment inward (see fig. 9).

This transport system caused a recurved spit, which after some time transformed to the present shape.

Because of the obliquely entering waves, some sand also comes along the coast from the north. This quantity is very limited (see also the chapter on coastal erosion around Porto). The sand from the north is transported by a longshore current due to the higher waves along the -5 m contour around Felgueiras.
It joins the sediment settled in area F.

Summarising, one may state that the waves cause a transport of sediment from area F via the Cabedelo to the head of the Cabedelo, and that the head will be built up in an easterly direction. If the head of the Cabedelo is turned to the west this head will be eroded. Due to waves, there is a small input of sand at the north side along Felgueiras, and a small output at the south along Seca do Bacalhao.

Very heavy storms cause not only a wave set up but also a wind set up. During such storms, much sediment is brought into suspension and transported by longshore currents and set up induced currents. The effect of mass transport by singular waves is less.

During a heavy storm, erosion mostly occurs on the higher sections of the beaches, especially in the area where the supply of sediment is small and the wave action heavy. Therefore, during extremely heavy storms, erosion of the Cabedelo near the Pedras do Maroica has to be expected.

If such a storm from a westerly direction, severe erosion of the head of the Cabedelo has also to be expected, if the head is turned towards the west.

During such storms there may be a breakthrough of the Cabedelo. Due to the normal circulation of sediment and currents, such a gap will be closed automatically by nature. Gaps south of the Pedras do Lima are completely unstable and are closed in a short time.
6. WAVES AND CURRENTS

In the previous chapters the influence of waves and currents have been treated apart. Of course they occur together. When there are periods of low river runoff, this means that during ebb the sediment from the Cabedelo is transported to area F, that it is transported by waves from area F towards the Cabedelo and accordingly to the north of the Cabedelo. Then the combined action of flood-current and waves transport the sand to the eastern side of the Cabedelo.

During a severe storm more sediment is transported towards the eastern edge of the Cabedelo than can be eroded by normal ebb current. Thus, as a result of tides, small river discharge and varying wave action, the head of the Cabedelo will be built up in an easterly direction.

During periods of high river runoff, in principle the same circulation pattern exists. Only the forces to build up the head of the Cabedelo in a westerly direction are stronger. Thus, as a result of a high water river discharge, the head of the Cabedelo will be built up towards the west.

Comparing these findings with the position of the Cabedelo in the last 100 years confirms the conclusion see fig. 10. During the last 40 years, the peak discharges of the river Douro were decreased due to the construction of the dams in the river. This resulted in a decreased supply of sediment to the system. In the past, the beach of the Cabedelo reached towards Seca do Bacalhao, and much sand was
transported along the beach towards the south. After the river's supply of sediment decreased, the southern edge of the Cabedelo suffered from erosion, because there was still a transport towards the south, but a decreased supply from area F. This process continued until the beach of Cabedelo was in its present position. Transport of sediment towards the south is now prevented by the rocks of Seca do Bacalhao.

The extreme flood of 1961/1962 was clearly an exception. During that winter the river—discharge was so high that the Cabedelo was flooded. After the flood the Cabedelo was closed again rather quickly, but a vast shallow area was formed west of the Cabedelo. In the following years this shallow area was removed by wave action. In 1964 (see fig. 11) the sand above the 0 m contour was completely moved away.

In history the usual position of the head of the Cabedelo was directed towards the west. In 1972 however, the Cabedelo had a position defined by relatively strong erosion in the previous years. In the years after 1972 one can clearly observe a movement of the head of Cabedelo towards the west, reaching a maximum in 1979 (see fig. 11). In the winters of 79/80 and 80/81 the river discharge was unusually low. The influence of the waves was therefore relatively strong, and the head of the Cabedelo moved towards the east (see fig. 11). This can also be seen in fig. 12. The upper photo (Jan. 1982) shows a shallow sand bank west of the Cabedelo. In the lower photo (June 1982) this sand bank has disappeared.

Although not quite clear, but also the movement of the 4 m contour line proves the above statements (fig. 13). In 1964 the remainings
of the 1962 flood can be seen in this figure, but in later years also the deeper sand was removed.

A more detailed drawing of the 4 m contours in the river mouth (fig. 14) surveyed in 1981 shows the seasonal influence. In summer (when there is no river runoff) the channel tends to get very shallow and narrow.

The extremely eastern position of the Cabedelo is certainly an exception, although the extreme western positions, as happened in the past, will not occur anymore, because of the peak shaving of the discharge by the dams in the river.
Along the coast south of Porto a severe erosion occurs, especially near Espinho. During the past, the construction of the port of Leixoes was blamed for this erosion. Although in a paper by Pires Catanho, Gomes, Mota Oliveira and Pinto Simoes presented at the PIANC conference in Edinburgh in 1980, it was already stated that this erosion is caused by the decreased sediment load of the river Douro and not by the port of Leixoes, many people in Portugal are still convinced that the erosion at Espinho is caused by Leixoes.

Along the coast of Portugal there is a very high sediment transport capacity. However, the supply from the north is insufficient to supply enough sand to transport as much as the capacity allows. Consequently a coast will erode, until the erosion is stopped by rock. North of Leixoes such an eroding situation has existed for years. Only small beaches between rock outcrops remain. Along this coast there is a small transport of relatively fine material. This transport is transported in a zone from the coast line to a depth where the biggest waves start to break (at a depth of approx. 10 m). The transport occurs during high wave action, when all the sand is brought into suspension. Then it is not hindered by the rock outcrops, and may pass to the south. In this way also, the port of Leixoes may be passed.

That the sand at Espinho is of a different origin than the sand at Leixoes can be seen in fig. 15. The median grain size at Espinho is 659 microns, while the median grain size north of Leixoes is 366.
microns. When the Espinho sand is compared with sand from the Douro, it shows the same characteristics. Consequently, the sand at Espinho comes from the Douro.

Due to the construction of the dams in the river, less sediment is supplied to the longshore current; the transport capacity is no longer completely used, and thus the coast will erode.

This subject has been studied in detail by Hidrotechnica Portuguesa for D.G.P. (Leixoes-Cabo Mondego; Problemas Litorais).

As a note for interest; if the erosion of the coast between the Douro and Espinho was caused by a catchment of sand to the north of Leixoes, then, north of Leixoes, a quantity of sand would be deposited, equal to the quantity that has disappeared from the beaches between the Douro and Espinho.

In that case, Leca de Palmeira would have one of the biggest beaches in the world.
FIGURE 1: DRAINAGE BASIN OF THE RIVER DOURÓ.
FIGURE 2: INFLUENCE OF DAMS ON RIVER DISCHARGE AND SEDIMENT TRANSPORT.
FIGURE 3: CURRENT AND SEDIMENTATION; FLOOD - CURRENT.
\[ t = 1 \]
\[ B = 2 \]

at these locations no velocity, only waterlevel rise

FIGURE 5: THE INFLUENCE OF RIVER DISCHARGE.
FIGURE 5: THE INFLUENCE OF VARIOUS RIVER DISCHARGES.
FIGURE 7: SLOPE OF THE CABEDELO DURING LOW WATER.
Figure 6. Sediment transport caused by waves.

- Main direction of incoming waves
- Transport due to longshore current
- Transport by singular waves
- Transport by set-up current
- Transport by smaller waves during high water

Area F
FIGURE 9: DEFORMATION OF THE HEAD OF THE CABEDELO.

erosion

accretion

transport by small waves

transport by setup-current
FIGURE 11: 0 m CONTOURS BETWEEN 1964 and 1980
FIGURE 13: 4 m CONTOUR LINES FROM 1964–1981
FIGURE 15: SEDIMENT DISTRIBUTION AT THE COAST NEAR PORTO.