LITTORAL PROBLEMS IN THE PORTUGUESE WEST COAST

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ABSTRACT

This paper summarizes a study recently concluded of a sandy coastal reach, 110 km long, on the portuguese west coast. The final objective of that study was the design of a sea defense master plan covering all the stretch, to be built at a long term. That coastal reach has been under a strong erosion process for a long time. The history of the problem and its present situation were thoroughly analysed. Different techniques, related to different aspects of the general problem (wave climate, littoral transport, sand bypassing, long term evolution under accretion or erosion conditions, groin field, spiral beaches, etc.) were used. In what concerns littoral transport and sand bypassing the improvement of currently available methods was tried. The need of an accurately defined wave climate was felt; some rather disappointing results can surely be related to the lack of accurate wave data.

1 - INTRODUCTION

The study deals with a coastal stretch 110 km long on the Portuguese west coast, limited to the north by the Leixões harbor and to the south by the Cape Mondego - FIG. 1. The stretch faces the North Atlantic Ocean, withstanding a severe wave climate. The Douro river, joining the sea just south of the town of Oporto, and the Aveiro lagoon entrance are the main geographical features of this coast.

From a geological point of view the stretch can be divided in three zones. The northern zone, only 4 km long, between the Leixões harbor and the Douro river, has a predominantly rocky nature. The second, 15km long, presents a series of rocky outcrops defining a series of sandy beaches of high recreational value due to their proximity to important urban areas. The third one, to the south of Espinho, is a long and almost straight sandy stretch of 90 km.

Some centuries ago this stretch suffered a period of alluvial over feeding. The lagoon of Aveiro was formed in that period, as a result of the southward growing of a sand spit - FIG 2. Concerning this subject , a very interesting paper (The History of a Tidal Lagoon Inlet and its

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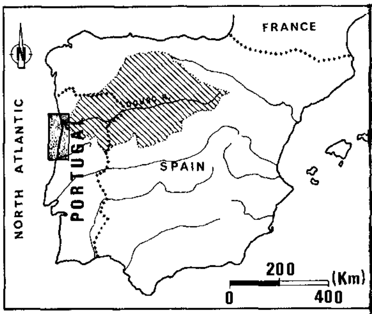
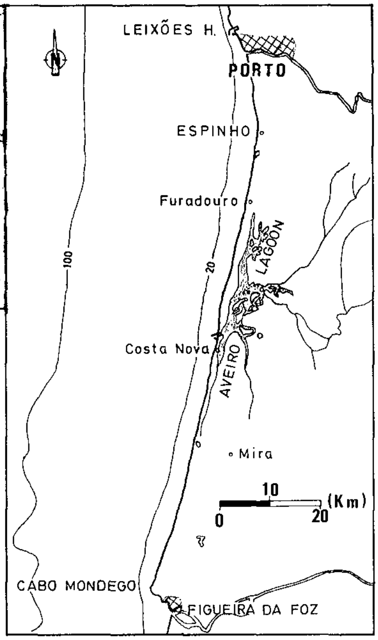


FIG 1 - Location map



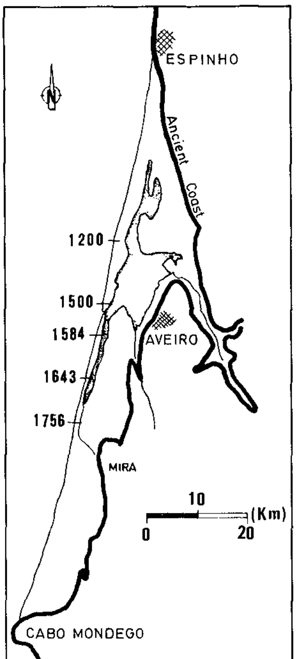


FIG 2 - Formation of the Aveiro Lagoon

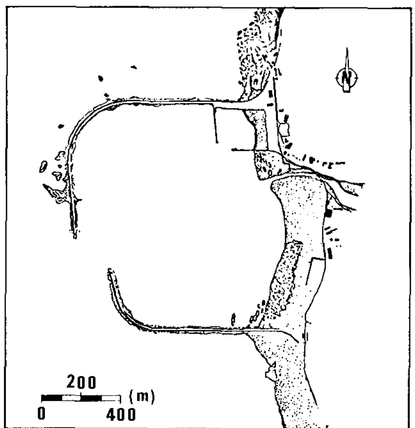


FIG 3 - Leixoes harbour. The 1892 layout

Improvement - the Case of Aveiro, Portugal) was presented by Abecasis , C.K. at the 5th Conference on Coastal Engineering, Grenoble, 1954.

In that paper a close relation between the above-mentioned phenomenon and the Douro river as an alluvial source is established. It has to be said that the phenomenon is not specific of this coastal stretch; in fact, one could refer to other cases of the same historical period around the Iberic Peninsula and even in the Portuguese coast, clearly demonstrating a situation of strong alluvial feeding. Although very interesting, the purpose of this paper is not the discussion of the causes which determined that situation.

The first records concerning the erosion process are 120 years old and concern Espinho and Furadouro which were, at that time, very small fishing villages in the northern area of the stretch - FIG 1. One is almost sure that the erosion process began earlier; however, human presence along the littoral area was almost null and the problem was not reported.

In 1892 the two long breakwaters of the Leixões harbor were completed - FIG 3. By those days the erosion process in Espinho had already begun at least 20 years ago. Even so, many people related and some people keep on relating the problems of Espinho with the construction of the port of Leixões.

The today town of Espinho has a long history of damages caused by the sea. Figure 4 registers the evolution of the water-line position (distance to a fixed point) in Espinho. We can see that from 1885 to 1910 (25 years) the coast receded 225 m (9 m/year). Even more striking is Figure 5, showing that the old village center was almost completely "swallowed" by the sea between 1880 and 1912. A historical photo taken on the 20th Dec. 1904 - FIG 6 - registers the falling down instant of the tower of Nª. Srª. da Ajuda church (see location on FIG 5).

From 1912 till 1929 the sandy coast recovered a lot, by reasons not clearly understood, although it had been related to the construction of three groins between 1911 and 1918, the first protection works ever built in the Portuguese west coast. Since then several improvements and extensions of the earlier protection scheme were performed: new groins, a sea-wall, etc. Although the town of Espinho had become really protected, the protection scheme couldn't avoid the withering of the sandy beach; by 1980 it had almost disappeared in front of the town.

A few other places along the stretch also have their historical evolution fairly well documented.

The zone just south of the Leixões harbor lost its only alluvial source, that is, the coast to the north, when the two breakwaters were built (1982). In fact, the retention effect upon the southward directed littoral transport and the dredging of the harbor entrance removed almost completely the sediment feeding of the stretch between the harbor and the Douro river mouth - FIG 1. The result has been the loss of some sandy beaches which, in the first decades of the century, were preferred by people of the northern area of the country.

The adjacent urban area remains naturally protected by the rocky coast; the landscape remains highly appreciated; but its recreational value is no longer the same as in the old days. At present, we begin thinking on the possibility of establishing artificial beaches taking advantage of natural rocky outcrops to be improved as littoral barriers, and doing some artificial sand filling.

Taking into account the history of a disappeared little church in Furadouro - FIG 1 - it seems that the coast receded some hundred meters, between 300 and 400 m, since the last decades of the 18th century till 1930.

Quite recently (1959) the construction of two jetties in the Aveiro lagoon entrance has caused important changes on the local littoral regimen, with a strong accretion in the northern stretch and strong erosions in the southern stretch - FIG 7.

It can be said that, at present, only the last southern 30 kilometers of the whole stretch do not present any erosion problem. That is the result of the retention effect on the Cape Mondego, acting like a big natural groin. But one can be sure that the problems will "propagate" to the south as time goes by.

Erosion is particularly threatning just south of Espinho and south of the Aveiro lagoon entrance.

Until now protection works have been built separately, at different points of the coast, whenever the risk of destruction of a particular urban area occurs, without a rational plan. A study was undertaken with the final objective of establishing a long term sea defense master plan covering the whole stretch.

2 - RECENT EVOLUTION. PRESENT SITUATION

2.1 - General characterization

By"recent evolution" one means after 1950. What differentiates this period from the previous one is the existence of data, namely topo-hydrographical surveys and aerial photos adequate to a quantitative evaluation of the coastal evolution.

Topo-hydrographical surveys concern only some places or some limited coastal stretches where erosion problems are relevant on account of the patrimonial or social importance of the littoral areas; the greater this importance, the better the data of this type.

For the whole coastal stretch, the best data we could afford were aerial photos, at different times. It was possible to analyse data of this type at intervals of more or less one decade, since 1947.

Initial fears about the accuracy of this approach were not confirmed. Some difficulties had been antecipated: the correct identification of the water-line on the beach slope; the correct identification of fixed references in remote and densely wooded littoral areas; and mainly the inaccuracy resulting from a changing tidal level (one photo taken during high-water over a beach of normal slope can display an "erosion" of some 30-50 m or even more when compared with another one taken during low-water, if the tide is 3-4 m high).

Nevertheless, the result was very coherent and encouraging. Figure 8 displays the coastal evolution south of Espinho and the Aveiro lagoon

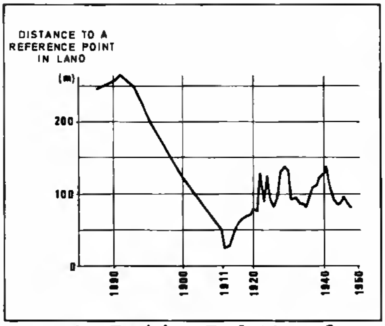


FIG 4 - Espinho. Evolution of the shoreline position

FIG 6 - Espinho, 1904. A church goes to ruins

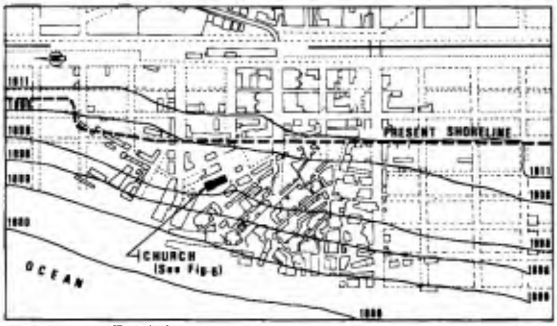


FIG 5 - Espinho. Coastal receding - 1880/1912

FIG 7 - The Aveiro lagoon inlet

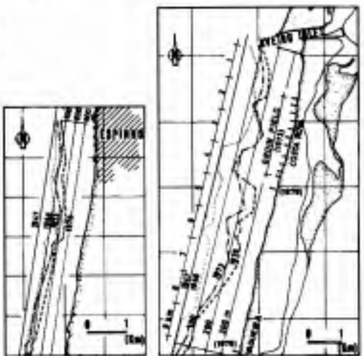


FIG 8 - Coastal evolution. Results from aerial photography analysis inlet (FIG 1) between 1947 and 1978, as obtained from aerial photo analysis.

Both places present maximum erosion rates of 8 meters per year (temporal mean values) during that period of 30 years; erosion was particularly severe in the periods 1947/58, south of Espinho, and 1958/73, south of Aveiro (following the construction of the jetties), with local rates higher than 10 m/year.

The results of some analysis show the erosion "propagating" to the south with time; during the seventies erosion problems were present along a distance of some 20 km to the south, with mean erosion rates of several meters per year.

2.2 - Specific Cases

2.2.1 - Introduction

Some specific cases have been deserving special attention since a long time, owing to the urban value of littoral areas affected by the coastal receding phenomenon or by some other reasons (e.g. Espinho, Aveiro lagoon inlet). Therefore, data are relatively abundant, specially in what concerns hydrographical surveys, which allowed the quantitative (volumetric) evaluation of the erosion process.

Nevertheless, some difficulties were encountered as a result of data deficiencies. By far, the most important one is related to the lack of information below the zero hydrographical level. In fact, most hydrographical surveys cover the areas above that level only, in practice above low water level. So, the volumetric evaluation of the specific coastal erosion cases concerns only the zone of the beach above datum level.

The evaluation was accomplished according to the following approach:
- beach profiles, with a 200 m spacing, were drawn;
- the corresponding areas (A) above zero datum level were evaluated;
- curves A (s) for each available survey were drawn, s being the abscissa along the beach;
- areas under those curves, representing sand volumes above zero level [$V = \int A(s)ds$] were measured;
- a curve V (t) was drawn, t being the time variable (years).

The evolution of the Aveiro lagoon outer bar was evaluated by comparing the hypsometric curves characterizing the global morphology of the bar in each date.

Some comments on the results obtained in two exemplifying cases (Espinho and Aveiro lagoon bar and adjacent littoral stretches) are added.

2.2.2 - The beach of Espinho

The beach of Espinho was divided into three stretches: A (375 m), to the north of the sea defense scheme; B (1500 m), corresponding to the sea defense scheme, which comprised a sea-wall and several short groins; C (625 m) to the south (downdrift) of that scheme. Figure 9 shows the evolution curves of stretches B and C.

Curve B displays an almost regular erosion rate of 18,500 m^3/km.year above zero datum level. On the contrary, curve C displays two different evolution periods: before and after middle sixties; the mean erosion rate raised from 19,500 m^3/km.year, in the first period, to 70,000m^3/km.year, in the second; in linear terms, coastal receding in this stretch raised from 2.3m/year to 9.2 m/year between the two periods; it should be noticed that in a period of 13 years (1964-1977) the coast receded 120 m in this stretch.

2.2.3 - Aveiro lagoon inlet area

The construction of the outer jetties of the Aveiro lagoon inlet (1950-58) determined important morphological changes in the surrounding areas: updrift and downdrift beaches and outer bar. Those changes were intensively analysed; we can only summarize here the most relevant results - FIG 10.

Nowadays, the accretion updrift zone is 8 km long. The weakening of the littoral transport and the intense extraction of sand for the construction industry led to the conclusion that the length of the above-mentioned zone may have stabilized.

The available hydrographical surveys cover a length of 3.5km and concern only the area above zero datum level. Therefore, for the evaluation of the accretion rates along the whole zone, some assumptions had to be considered.

Erosion problems in the downdrift (southward) beaches began even during the construction of the outer jetties. By the end of the sixties coastal receding had begun endangering the summer resorts of Barra and Costa Nova. From 1972 to 1973, a groin field (11 groins), protecting a beach length of 2,400 m, was built; of course, the erosion process continued very active to the south. In 1979, two long groins (250 m) were built, one just south of the village of Vagueira, the other as a complement of the previous groin field. Nowadays, erosion problems are felt south of Vagueira, in a coastal length of several kilometers.

The construction of the outer jetties also induced important changes, both on the outer bar and the lagoon channels.

Curves on Figure 10 characterize some of the main effects of the morphological evolution of those three zones: updrift and downdrift beaches and outer bar.

The accretion rate in the updrift zone above datum level displays strong interannual irregularities. Nevertheless , since the end of the sixties it shows a regular decreasing trend, which can be related to the position of the low-water line vis-à-vis the north jetty head. In the first three years the rate was particularly high: 800,000 m^3/year. Such a value led us to think, for the first time, that the mean annual littoral transport could overpass the value of 10^6 m^3, usually accepted for this coastal stretch.

Taking into account the storage under the zero datum level, a mean storage rate of 600,000 m^3/year, for the whole period (1950-1978) was found; if one also considers the sand extracted for the construction industry, it means that a volume of about 20 million m^3 has been subtracted form the natural littoral process, since the beginning of the construction of the jetties (1950). This event fully explains the erosion problems felt in the downdrift beaches.

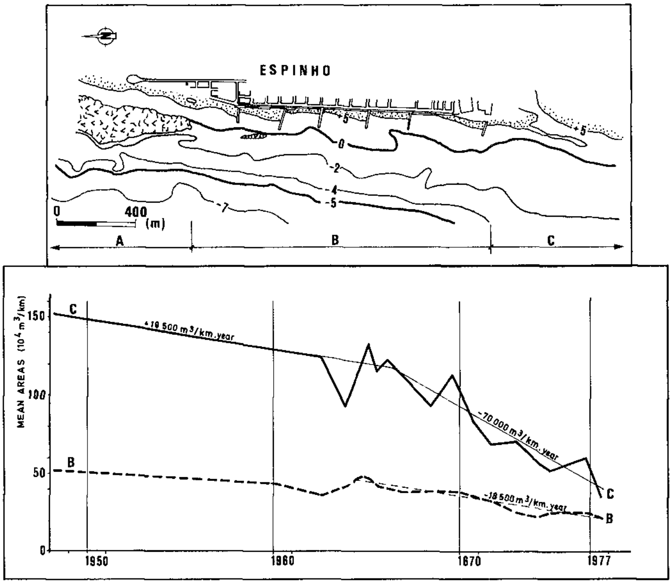


FIG 9 - Espinho beach. Evolution after 1950

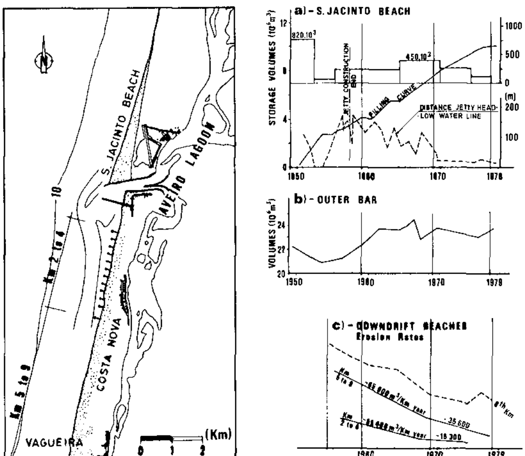


FIG 10 - Aveiro lagoon inlet. Evolution of the surrounding areas after 1950

The volumetric evolution of the outer bar displays a first withering phase (4 years) followed by recovering and stabilizing periods. This situation can be related to the advance of the northern jetty during the construction phase and to the rate of bypassing of this structure. Qualitatively, the stabilization of the outer bar and the decreasing of the accretion rate in the updrift zone can be correlated.

The erosion process in the downdrift beaches was analysed in detail, taking into account stretches 1 km long, afterwards combined into larger stretches with a particular physical meaning (e.g., stretch protected by the groin field, stretch influenced by the outer bar). The volumetric evolution presents irregularities throughout the years, as exemplified on Figure 10 with the 8th km curve. Nevertheless, one can clearly distinguish two periods concerning erosion rates above zero datum level. Curves on Figure 10 pertain to the stretch which is more directly influenced by the outer bar (from kms 2 up to 4), as well as to the downdrift stretch (from kms 5 up to 9). Erosion rates on the former has always been smaller than on the latter. That can be related to the known trap effect exerted by a big outer bar; nevertheless, any of them displays a clear reduction of the erosion rate in the last years. Again, one can correlate this erosion rate reduction, the stabilization of the outer bar and the decreasing of the accretion rate on the updrift zone.

Some other relevant results can be presented as follows:

- in the period from 1954 to 1978 (24 years), the mean coastal receding along the whole stretch (9 km) amounted to 150 m;
- during a period of two years after the construction of the groin field, the adjacent southward stretch (1750 m) receded 50 m;
- during a period of 15 years (1954-1969), the stretch south of the groin field (from kms 5 up to 9) lost 5 million m^3 of sand above the zero datum level.

3 - LITTORAL PROCESS

3.1 - Introduction

Several studies concerning the littoral process of the Portuguese west coast were carried out, namely the evaluation of the strength of alluvial sources, the evaluation of the littoral transport, the mathematical modelling of coastal morphological changes and the determination of the equilibrium beach line orientation.

3.2 - Alluvial sources

The almost exclusive alluvial sources of the coastal stretch between Leixões and Cape Mondego have been the coast north of Leixões and the Douro river. For a coast in a dynamic equilibrium state, the evaluation of the strength of those sources would be equivalent to the evaluation of the littoral transport.

The coast north of Leixões harbour is fed by several rivers. River Minho is the most important one. It constitutes border between Portugal and Spain (FIG 11). Surely the sediments carried by these rivers are transported to the south. Before the last decade of the 19th century, when the breakwaters of Leixões harbor were built, those sediments ente red the stretch under analysis; since then they have been dredged at the entrance of that harbour.

Taking advantage of the long dredging record available, and discarding the fine fraction of the dredged material (normally absent from the littoral drift), it was possible to conclude that the littoral transport coming from the north coast would have been of the order of 150,000-180,000 m^3/year.

In what concerns the Douro river, two approaches were used. The first one took into account the above result and the areas of the catchment basins geologically suitable for the "production" of sand. A detailed survey of the available geological charts was made in order to identify those areas in the Douro river catchment and in the river basins tributaries of the coastal stretch north of Leixões. In this approach some assumptions were made: over the several basins, the mean rainfall regimen, the forest and agricultural occupation and the mean orographical (sloping) conditions are nearly the same.

Considering these assumptions, the strength of the updrift coast, as an alluvial source, would have been, previous to any human interference, of the order of 15 to 20% of that of the Douro river. Taking into account the littoral transport concerning the coast north of Leixões (150,000-180,000 m^3/year), it was concluded that the Douro river would have produced, in natural conditions, a mean annual volume of beach material of 0.75 to 1.2 million m^3. This means that a total mean annual volume of 0.9 to 1.4 million m^3 entered the stretch under analysis. This result fits quite well the currently accepted mean annual value of the littoral transport in this zone of the Portuguese west coast ($10^6 m^3$).

However, another approach for the evaluation of the Douro river strength as an alluvial source produced a much higher result. Four different theoretical bed load formulas (Dubois, Meyer Peter-Müller, Einstein-Brown and Engelund-Hansen) were used together with three different mean annual hydrological regimens: the natural, previous to the first important dams (before 1930), the present and the future one, when the plan for development of the Douro river basin will be fully implemented.

As usual, the scattering of the results is considerable. For instance, for the natural hydrological regimen the results were as follows:

	($10^6 m^3$/year)
Dubois	1.4
Meyer Peter-Müller	0.7
Einstein-Brown	3.5
Engelund-Hansen	1.8

In any case the Einstein-Brown value was much higher than the others. Besides, it exceeds largely the commonly accepted value for the littoral transport (10^6 m^3/year); therefore, it was discarded. Taking into account the average value of the remaining three formulas, the following results were obtained (10^6 m^3/year):

* natural regimen 1.8
* present situation 1.3
* after the conclusion of the Crestuma dam, under construction near the upstream limit of the Douro estuary 0.25

Considering the above natural regimen results and the littoral drift coming from the updrift coast, one gets a value of the order of 2 x 10^6 m^3/year. This rises the idea that the potential transport capacity of the wave climate is significantly higher than it is commonly accepted.

The coastal alluvial feeding is directly influenced by the extraction of sand for the building industry; its importance is even higher than initially suspected. It's rather difficult to assess correctly the importance of this activity, owing to the more or less uncontrolled way under which it was exerted during a long period. Direct inquires along the lower reach of the Douro river were made and the scarce records were searched and analysed.

Since 1980, this activity is generally forbidden along the Portuguese coasts, with the exception of a few very specific places. One of these places is the accretion zone updrift of the jetties of the Aveiro lagoon inlet (S. Jacinto beach - FIG 10); in the last years the extraction rate increased considerably in this area, amounting to 400,000 m^3, in 1980.

Nowadays, along the lower 50 km reach of the Douro river, including its estuary, sand and gravel extraction seems to be of the order of 1.5 x 10^6 m^3/year.

3.3 - Littoral transport

3.3.1 - Sediment budget concept

For the evaluation of the littoral transport two approaches were used: the sediment budget concept in successive cells from north to south and the CERC littoral transport formula, using the available wave climate.

To apply the first approach, the coast between Espinho and Cape Mondego was divided into 5 cells. In this analysis the stretch Leixões--Espinho, with a predominantly rocky nature, and therefore in a sedimentary equilibrium state, was discarded.

A lot of work had to be done in order to evaluate the erosion (or accretion) inside each cell, since 1950. Some specific places have been morphologically surveyed quite regularly but, most of the time, above the zero datum level only. In those places assumptions for the relation between the erosion cross-section areas above and under datum level had to be made.

Nevertheless, for most of the stretch Espinho-Cape Mondego only the successive positions of the beach line, as registered by aerial photography, were known. At this point, an important step of the study was to establish an erosion profile. A mixed type profile was adopted: rectangular above, trianguler under the zero datum level - FIG 12. Site inspection and topographical data allowed the knowledge of the upper level of the erosion profile, i.e., the level of the littoral dunes under erosion (FIG 12, dimension A). On the other hand, taking into account some available hydrographical surveys extending to underwater areas, the lower level of the erosion profile could be established (FIG 12, dimension B). B values varying from 7.5 m up to 9.5 m between Espinho and Cabo Mondego were adopted.

Wind action is surely irrelevant in the littoral process of this particular case. Sand losses to deeper areas, due to transversal movements, were also discarded.

Boundary conditions concerning the littoral drift flowing through the cross-section of Espinho (X m^3/year) had to be established. Taking into account the results concerning the alluvial sources, the following values were assigned to the X variable

Period	X(m^3/year)
1950/59	800,000
1960/64	600,000
1965/69	400,000
1970/74	250,000
1975/78	100,000

Figure 12 presents the final result of this approach concerning two sections: one at the updrift limit of the accretion zone of the Aveiro lagoon inlet; the other at Cape Mondego. This figure warrants the conclusion that the potential littoral transport capacity of the wave climate seems to be of the order of 2×10^6 m^3/year. The littoral drift flowing through the section of Espinho being much smaller, the wave climate "nourishes" itself with the sand deposits (beaches) of the southward stretch; nevertheless, the stretch Espinho-Torreira doesn't seem big enough to saturate the potential transport capacity of the wave climate; in fact, the mean value of the littoral drift flowing through the cross-section of Torreira seems to be of the order of 1.5×10^6 m^3/year. Another interesting result of this approach concerns the natural bypassing of the Aveiro lagoon inlet. It seems that, nowadays, it remains of the order of several hundred thousand m^3/year, despite the storage on the updrift accretion zone, the extraction of sand in that zone and the weakening of the alluvial sources.

3.3.2 - Theoretical evaluation

The CERC littoral transport formula was used. Despite the amount of work developed in this analysis, the results were quite disappointing. In the next paragraphs the studies developed are summarized.

With some well-known assumptions concerning the breaking region, the CERC formula may be written as follows:

$$Q_s = 750\, H_b^{5/2} \sin 2\alpha_b \qquad (1)$$

Q_s being evaluated in m^3/hour and H_b being the root mean square breaking height.

The available wave climate data were recorded in a 6 year period (1954-60) in Figueira da Foz, a summer resort located just south of Cape Mondego. Based on this data, the mean annual deepwater wave conditions can be characterized in terms of frequence distributions of directions, periods and heights. Considering the results of some previous studies based on these data, some difficulties were expected since the beginning.

For the discretization of the wave climate, seven directions (from SSW to NNW), eleven heights (from 0.75 up to 10.5 m) and three periods (8, 11 and 14 s) were considered; that formed a set of 231 "waves" (7 x 11 x 3) characterizing the mean annual wave conditions. A computer program was prepared for the evaluation of the gross and net transport capacities of these "waves".

Another computer program performed refraction diagrams between deep water and the (-5.00 m) contour line. Shoaling (K_s) and refraction (K_r) coefficients and directions (α) at the (-5.00 m) contour were assigned to each "wave" as input of the littoral transport program. To apply Equation (1) breaking values (H_b, α_b) area needed; however, only some particular "waves" will break at a (-5.00 m) position.

The smaller the wave height, the nearer to the beach it will break and, therefore, the greater the refraction effect. This means that the period (T) and the deep water wave direction (α_o) are not sufficient to define α_b , K_s and K_r at the breakers, the problem being of an implicit type: α_b and H_b depend on the refraction effects but, on the other hand, these effects also depend on the wave height.

To solve this problem, the following approach was used:

- Snell's law was considered valid between the (-5.00 m) contour line and the breaker line

$$\frac{\sin\alpha_b}{C_b} = \frac{\sin\alpha_5}{C_5} \quad (2); \qquad Kr_{5-b} = \sqrt{\frac{\cos\alpha_5}{\cos\alpha_b}} \quad (3)$$

- Phase velocity follows the solitary wave theory

$$C = \sqrt{g(d + H)} \qquad (4)$$

- Breaking criterium: $H_b = d_b$ (5)

- Wave shoaling: as given by the linear wave theory for shallow water

$$Ks \simeq 0.5 \frac{\sqrt{T}}{\sqrt[4]{d}} \qquad (6)$$

Applying Eq. (6) at the (-5.00 m) position and on the breakerline, the shoaling effect between them will be

$$Ks_{5-b} = \sqrt[4]{\frac{d_5}{H_b}} \qquad (7)$$

Combining Equations (2), (3), (4), (5) and (7) we get

$$\alpha_b = \text{arc sin } \left(\sqrt{\frac{2H_b}{d_5 + H_5}} \cdot \sin\alpha_5 \right) \qquad (8)$$

$$H_b = \sqrt{\frac{\cos\alpha_5}{\cos\alpha_b}} \cdot \sqrt[4]{\frac{d_5}{H_b}} \cdot H_5 \qquad (9)$$

In these equations d_5 equals 5 m plus the tidal level. Equations (8) and (9) are solved iteratively. For the starting step, to obtain a first approximation of α_b and H_b , H_b takes the value of H_5.

Example: with a 2 m tidal level, d_5 = 7 m; let us consider three waves with $\alpha_5 = 10^o$ and H_5 = 5 m; 3 m; 1 m; according to this approach, breaking heights and directions would be

H_5 (m)	5	3	1
H_b (m)	5.36	3.56	1.49
α_b	9.4°	8.4°	6°

The first results obtained with the littoral transport computer program were absolutely unacceptable. In fact, a northward net littoral drift of 1.1 x 10^6 m^3 was obtained, and it's known for sure that the net littoral drift is southward directed.

Such a result seems to mean that the available wave climate is southward biased, i.e., the true wave climate must be richer in waves coming from the north-west quadrant. Therefore, several tryings were made aiming to "construct" a more likely wave climate; this was accomplished by transferring occurence percentage values, for instance, from W to NNW.

Two measures of its likeliness were available:

- the wave climate has to produce a southward net littoral drift;
- the same wave climate, acting over a coastline making an angle of some degrees with the true coastline, would produce a zero net littoral drift (according to the studies presented in item 3.5, in the area of Aveiro this equilibrium angle would be of the order of 4° to 6°).

Eight wave climates were "constructed" this way; Figure 13 presents two wave roses, one concerning the original wave climate (Cl_0) and the other one related to the northmost biased wave climate (Cl_8). Four coastline directions were considered: the true coastline and three others making angles of 2°, 4° and 6° with the real one (in these tryings the beach was "rotated" above the (-5.00 m) level, only). For each wave climate and for each coastline direction, the gross and the net littoral drift were evaluated.

Despite the amount of work developed, the results were inconclusive. For instance, for an intermediate wave climate, labeled Cl_4, one got (values in $10^6 m^3$/year):

	True coastline	Beach angle with the true coastline direction 2°	4°	6°
Gross littoral drift	13.1	12.0	11.6	11.6
Net littoral drift	-4.4	-0.6	+3.2	+7.1

(minus signal means "southward directed").

We recall that the true wave climate would produce a zero net littoral drift for an angle of 4 to 6 degrees. According to the above results the Cl_4 vanishing angle would be 2.3° only; nevertheless, the same Cl_4, acting over the true coastline, produced an unacceptable high value for the net littoral drift.

We notice that the "rotation" of the coastline produces a minor effect over the gross littoral drift; on the other hand, the net littoral drift displays a great sensitiveness to that "rotation".

It seems unquestionable that these difficulties result mainly of inaccuracies of the available wave climate data. But one also has to keep in mind that "even with exact wave data, it is believed that the longshore transport can only be predicted within approximately -67% to +200%" (Dean, 1978).

3.4 - Mathematical modelling of morphological changes

A mathematical model was prepared with two main objectives: the study of the coastal evolution in the stretch south of Espinho and the foreseeing of the expected changes of S. Jacinto beach, as a result of another extension of the length of the north jetty of the Aveiro lagoon inlet; if the model had proved well, it would have been used in the planning of the sea defense scheme. However, the results were not satisfactory, mainly on account of inaccuracies of the wave data.

Basically, the mathematical model uses the approach of Willis and Price (1975). Two complementary devices were added: one takes into account the influence of the morphological changes on wave refraction effects; the other aims to simulate the bypassing process around a littoral sediment barrier.

One knows that a short term accretion or erosion will only affect the beach profile above a relatively high level in a shallow water region. Therefore, wave refraction effects will change only in a relatively narrow strip, adjacent to the shoreline; thus, it is not worthwhile to elaborate again all the refraction diagrams, specially when dealing with a more or less straight shoreline, in order to account for those changing effects.

The objective of the proposed approach is the evaluation of the breaking angle α_b at the modified shoreline. For that purpose, an equation of the following type is currently used

$$\alpha = \alpha_o - \text{arc tan} \frac{\partial y}{\partial x} \qquad (10)$$

α_o being the angle relative to the initial undisturbed shoreline.

The starting data for the proposed approach are the breaking wave height and the angle (H_b, α_b); they are available as output of the computer program described in item 3.3.2. In the region affected by the morphological changes the validity of equations (2), (4) and (5) is again assumed.

Knowing the breaking values of H and α, one goes back to an undisturbed depth, that is, a depth not affected by the short term morphological changes (for instance, d = 8 m under the reference level). Combining equations (2), (4) and (5) it is found

$$\alpha_{d.o} = \text{arc sin} \left(\sqrt{\frac{d + H_b}{2H_b}} \cdot \sin\alpha_{b.o} \right) \qquad (11)$$

$\alpha_{b.o}$ being the breaking angle relative to the initial shoreline, and $\alpha_{d.o}$ the corresponding value at an undisturbed depth (d). In this approach the wave height variation was neglected.

"Rotating" the shoreline

$$\alpha_d = \alpha_{d.o} - \text{arc tan} \frac{\partial y}{\partial x} \qquad (12)$$

being α_d the wave angle relative to the "rotated" shoreline, at an undis turbed depth (d).

Reversing equation (11), the angle at breaking position can be found

$$\alpha_b = \text{arc sin } \left(\sqrt{\frac{2H_b}{d+H_b}} \cdot \sin\alpha_d\right) \qquad (13)$$

Summarizing, in the proposed approach equation (10) is replaced by equations (11), (12) and (13). Let us consider a breaking wave 2 m high, with $\alpha_{b.o} = 5^o$; if the shoreline rotates 2^o, as a consequence of an accretion process, equation (10) will give $\alpha_b = 3^o$ while the sequence of equations (11), (12) and (13) will give $\alpha_b = 3.67^o$ (considering d = 7 m as the undisturbed depth).

To simulate the bypassing process another device was used: it relates the bypassing rate with the position of the surf zone vis-à-vis the head of the littoral barrier - FIG 14.

For the distribution of the littoral transport capacity across the surf zone, a triangular type law was assumed, with its maximum value at the breaker line. Equation (5) was again adopted as the "breaking criterium". The width of the surf zone (B) for the used assumptions depends on the breaker depth (d_b) and on the bottom slope. Therefore, a bottom profile had to be assigned to the breaker region in each specific case; in the case of the Portuguese west coast one of the mixed type was adopted-FIG14.

When the wave breaks landward of the littoral barrier head, bypassing doesn't occur ($Q_{bp} = 0$); if it breaks seaward, the bypassing rate will be a fraction of the littoral drift arriving at the barrier (Q), that fraction corresponding to the part of the triangular transport diagram which is not intercepted by the littoral barrier. That is (FIG 14)

$$Q_{bp} = \left[1 - \left(\frac{X}{B}\right)^2\right] . Q \qquad (14)$$

X being the distance from the waterline to the head of the littoral barrier.

Some difficulties were encountered in defining a Q with a physical meaning (the littoral drift arriving at the barrier). For instance, if Q is related to the orientation of the shoreline in the adjacent stretch, and if this stretch is a fixed number of integration steps Δ s long, then the bypassing rate depends on the integration step Δs. Finally, Q was related to the orientation of an adjacent stretch with a fixed length exceeding the surf zone width of the highest waves (for instance, 400m).

Difficulties of another type were risen when the accretion-erosion effects reached the limits of the mathematical model stretch; boundary conditions such as Y = const or Q_S = const were no longer valid. Besides, in the present case accretion caused by an artificial barrier occurs over a shoreline under a general erosion process. It seems that, in such a case, the best approach would be, like in other fields, to obtain the boundary conditions as output of another far-field model, covering a much longer coastal stretch.

To test this model the accretion process of S. Jacinto beach (2.2.3) was simulated between 1950 and 1978. The results were not satisfactory.

One should be reminded of the presumed inaccuracies of the mean annual wave climate used in the whole study. However, the accretion process

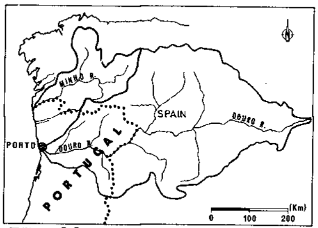


FIG 11
Stretch Leixões-Cabo Mondego
Alluvial sources

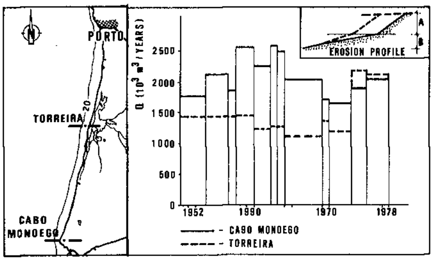


FIG 12 - Results of the "sedimentary budget" analysis

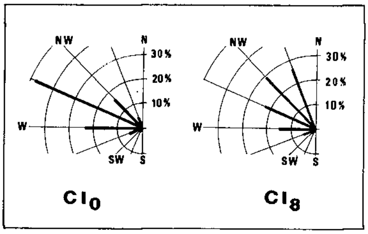


FIG 13 - Cl_0 and Cl_8 wave roses

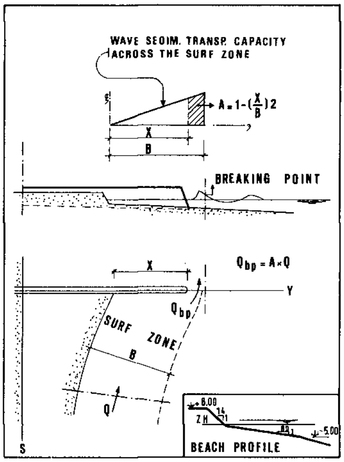


FIG 14 - Bypassing process of a littoral barrier

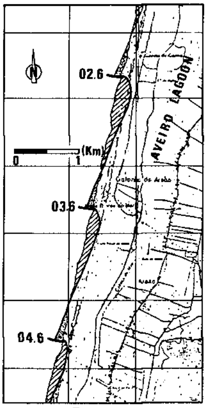


FIG 15
Sea defense plan.
Some typical structures

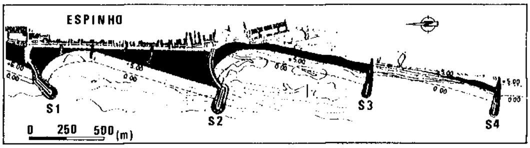


FIG 16
Beaches of Espinho.
Proposed protection plan

to be tested has been the result of wave conditions changing year after year. In fact, the true wave conditions that determined the accretion process of S. Jacinto beach are unknown. Besides, the accretion process reached the updrift model boundary much faster than in the prototype. These may be some of the reasons of the above-mentioned difficulties.

3.5 - Equilibrium beachline orientations

It will be seen further on that the sea defense master plan was designed for a zero net littoral drift condition. Therefore, the assumed beaches that will be formed between coastal protection works, will present shapes and positions corresponding to an equilibrium state. When foreseeing those beach forms, the evaluation of the equilibrium orientation of some existing beaches was very helpful. Such an approach assumes the existence of a dominant deep water wave direction characterizing the whole stretch. If that existed, one could determine the equilibrium orientation of any beach along the stretch.

Three beaches were selected for this study (FIG 1): Leça, just north of the breakwaters of Leixões, Espinho and S. Jacinto.

The first one can be considered almost in a equilibrium state, due to the relatively weak littoral drift arriving from the north. Taking into account two available hydrographic surveys, one determined a mean value $\theta_b = 13.5^o$, θ_b being the beach angle with the north-south direction.

The beach of Espinho has not surely been in a equilibrium state. Surveys made at 14 different times were carefully analysed. Two particular stretches of the beach were considered, each one on the updrift side of old groins. Based on this analysis a value $\theta_b = 17.5^o$ was adopted.

Nowadays, the S. Jacinto beach is 8 km long and it is not in an equilibrium state for sure. For the evaluation of the equilibrium angle, only the 500 m long stretch, adjacent to the north jetty of the Aveiro lagoon inlet, was considered. Hydrographic surveys were analysed at 37 different times. A value $\theta_b = 22^o$ was adopted.

Considering the results of the refraction diagrams, the following dominant deepwater wave directions θ_o were obtained (when wave periods of 10 to 12 s are considered):

Angles with N - S direction

	b	o
Leça	13.5^o	$37^o - 45^o$
Espinho	17.5^o	$38^o - 50^o$
S. Jacinto	22.0^o	$43^o - 50^o$

The results agree fairly well with one another, despite the fact that the stretch Leça-S.Jacinto is 60 km long. Therefore, a deepwater dominant direction $\theta = 50^o$, with a wave period T = 12 s, was adopted for the whole stretch. The corresponding θ_b equilibrium values along the stretch, necessary for the sea defense planning, were determined using the results of the refraction diagrams.

4 - SEA DEFENSE PLAN

The plan includes more than 60 structures, almost exclusively of the groin type.

In the northern zone, between Leixões and Espinho, the spacing and the length of the coastal structures are quite variable. This results from the occurence of many granitic outcrops that ought to be used to anchor the groins. In this northern zone the coastal structures will have an almost unique objective which consists of improving the existing beaches. In fact, the defense of the coast is insured by its rocky nature.

A sandy coast extends to the south of Espinho with long reaches of dunes, sometimes bordering pine forests, other times facing little towns and villages. Wherever the littoral areas have a low patrimonial value, the spacing between coastal structures is relatively large (2 km and even more). This means that some additional erosion, in some specific points of the coast, will have to be accepted; on the other hand, the number of coastal structures, always very expensive, becomes quite reduced. Figure 15 displays the proposed solution for a stretch of beach located between Aveiro and Mira. In such a case the plan took advantage of the spiral beach concept, studied by Silvester (1972) and others.

Wherever the coastal receding had to be stopped, on account of the high patrimonial value of the littoral areas, the plan used the groin field concept, in which the accretion zone of a groin reaches the updrift one. The results of experimental studies carried out at LNEC (Civil Engineering National Laboratory, Lisbon) were used. According to Barcelo' (1969) the ratio D/C varies with α as follows

α	D/C
20^o	2.5
15^o	3.5
5^o	4.0

D being the groin spacing, C its lenght and α the angle between the crest of the dominant wave and the shoreline.

In order to reduce the number of coastal structures a large spacing (D) was adopted; current values for D and C have been D = 875 m, C=250m.

Figure 16 presents four structures protecting a coastal length of 3 km. They have been the first sea defenses of the whole plan to be built; presently (summer, 1982) its construction is about to be concluded. The objectives of the structures labeled S1 and S2 are twofold: to defend the town of Espinho and to restore its old importance as a summer resort. This explains the length of the groins S1 and S2. They were planned to trap a "spiral beach" 1,200 m long. During the last year more than half a million m^3 of sand was naturally accumulated between S1 and S2.

5 - CONCLUSIONS

Coastal erosion became a major problem of almost every coast. The main reason for such a situation is the weakening of the alluvial sources, due to the improvement of the river basins. Human activity along the coasts often aggravates the situation by diverting the natural path of the littoral sediments. Therefore, in many instances, it seems advisable to consider the long term vanishing of the littoral transport when planning a sea defense scheme.

Mathematical modelling of littoral evolution requires two main work bases: accurate wave data and a dependable littoral transport formula. If wave conditions are very variable in what concerns either heights, directions or periods, the difficulties faced when defining accurately a wave climate may be higher than those of elaborating a mathematical model. In such a case, a mathematical model seems to be a too sophisticated tool, leading to disappointing results. That has been the case on the studies undertaken concerning the littoral problems of the Portuguese west coast.

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