LITTORAL TRANSPORT UNDER COMPLEX WAVE FIELDS: PECÉM, NORTH EAST BRAZIL

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Abstract

In connection with the design of new marine facilities a hydraulic study was carried out at Pecém, NE Brazil. The project comprised mathematical modeling of waves, nearshore hydrodynamics and sediment transport before and after the construction of the offshore harbor in front of Ponta do Pecém. The wave conditions are characterized by the simultaneous occurrence of sea and swell from different directions. The littoral current generated by the sea becomes detached at the headland. A shore-connected spit develops under these circumstances. During periods of predominant swell the spit erodes. The main impact of the harbor is a further reduction of the littoral drift W of the headland, which causes increased sediment accumulation immediately W of the headland and coastal erosion W of the city of Pecém.

Introduction

Presently an offshore harbor is being constructed in front of the city of Pecém, approximately 40 km west of Fortaleza in NE Brazil, see Fig 1. The harbor is located approximately 2 km offshore. In connection with the design of the new marine facilities, a coastal impact assessment was carried out (Danish Hydraulic Institute 1997). The location of the harbor is shown in Fig 2

The coastline of Ceará is characterized by curved sandy beaches, interrupted by small rocky headlands. The beach material consists of medium to fine sand with a median grain size of the order 0.25-mm. Since several years the coastline in front of Pecém is subject to

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erosion. An analysis of aerial photographs has revealed that the coastline in front of the city has retreated with approximately 50 meters during the last 25 years. The coastline erosion is not homogeneous along the coast but varies from approximately 4 m/year at the western edge of Pecém to approximately 2m/year at its eastern boundary. Approximately 500 m further towards west, a slight beach accretion was observed locally.

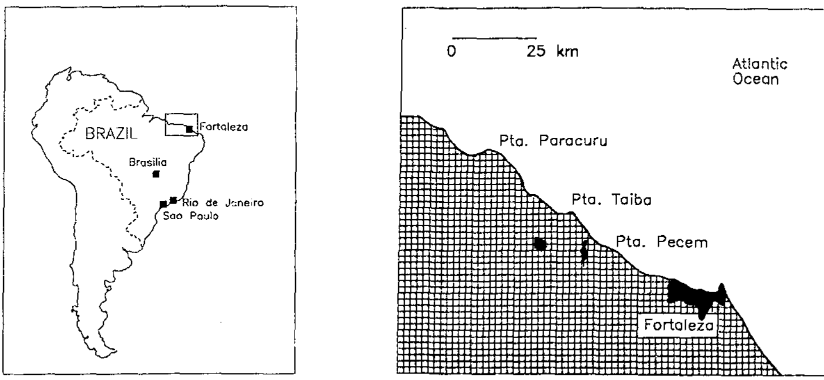

Fig. 1 Location of the project site

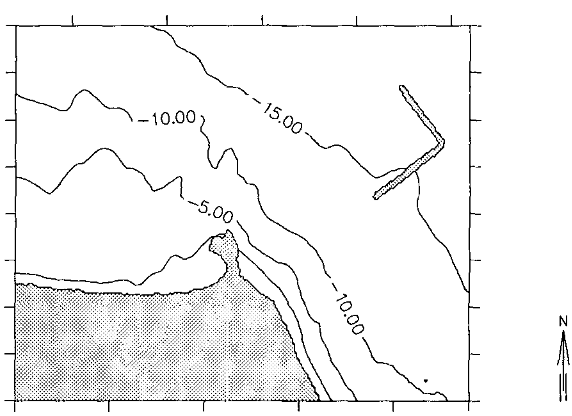

Fig. 2 Location of the new offshore harbor of Pecém scale 1: 60,000.

Variations in the coastline position occur during the year. In the period from November until April, beach erosion occurs due to swell coming from the Northern Hemisphere. During this period rock is exposed at many locations at the beach. From May until November, the wave conditions are dominated by sea waves.

The project site is characterized by a stable wind climate. The wind speed and directions are fairly constant through the year. The main wind direction is E-ESE. The most frequent wind speed is 6 - 8 m/s from E.

Along the entire coastline, high eolian dunes extend to several kilometers away from the coast and form a dominant morphological feature of the landscape. The height of the dunes exceeds 30 m in some locations. Their orientation corresponds to the prevailing wind direction, which is approximately 95° N. The dunes consist of marine sand with a slightly better sorting than the beach sand. Close to the shoreline, the dunes are active. Aerial photographs show that the dunes migrate with an average speed of approximately 6 to 7 m/year. The older dunes further away from the coastline are fixed by vegetation. Depending on the coastline orientation, the coastal dunes act as a sink of sediment in the coastal sediment balance. Due to the dominating winds from easterly directions and the coastline configuration at Pecém, sediment loss due to wind transport is only of importance at the eastern side of Ponta do Pecém.

The wave conditions are characterized by the simultaneous occurrence of swell and sea from different directions. Sea approaches the coast at Pecém under large angles. Due to refraction and diffraction around the headland, a part of the wave energy reaches the shore. The area E of Ponta do Pecém is considerably more exposed to the action of sea waves than the western side.

Although the tidal range is approximately 3 meters, tidal currents are very weak, of the order 0.1 m/s. These currents are of minor importance for the nearshore sediment transport. The main effect of the tides is the cross-shore shift of the sediment transport patterns, which is dictated by the water levels. During ebb, wave breaking occurs on the shoals in front of the city of Pecém at a distance of several hundred meters off the coast. During flood, the headland becomes partly inundated.

Wave conditions

Between 1991 and 1995 INPH has carried out wave measurements in Fortaleza by means of a Wave rider located at a distance of approximately 1 km offshore of the port of Mucuripe. The wave buoy was located at a water depth of 15 m. (INPH 1986a).

Since March 1997 wave data has been recorded with a directional Wave-Rider, which is located approximately 4 km offshore of Pecém in a water depth of 17m. These measurements provide detailed information about the spectral characteristics of the wave conditions. In order to obtain reliable statistics, measurements carried out over several years are necessary. However, the wind conditions at the present site are fairly constant throughout the year. The measured wave height statistics showed good agreement with the data from Mucuripe and were assumed representative for the present site.

Fig. 3 shows an example of a measured wave spectrum at Pecém. A clear bimodal distribution of the wave energy distribution can be noticed. The first peak occurs at frequencies of approximately 0.06 to 0.1 s^{-1} corresponding to wave periods of 10 to 16 s. The mean direction of the waves with these frequencies varies between approximately 20° N and 45° N. These waves represent the swell originating from the Northern Hemisphere. The second peak represents sea, with frequencies typically in the order of 0.12 to 0.3 s^{-1}, corresponding to wave periods of 3 to 8 s. The direction varies between approximately 75° N and 120° N.

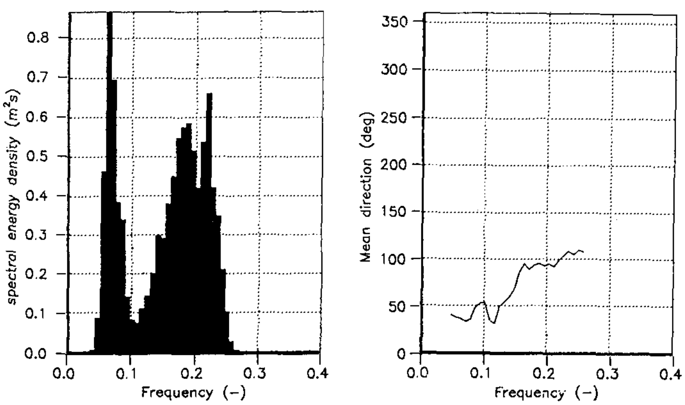

Fig. 3 *Typical wave spectrum at Pecém. Two distinct peaks can be observed with frequencies of approximately 0.08 and 0.12 s-1 representing swell and wind waves (sea) respectively. The wave directions of the two dominant wave components are varying from approximately 30° N for the swell to approximately 120° N for the sea waves.*

The usual way to apply the wave data in coastal studies is to represent the wave spectrum by a few statistical parameters. Typically the significant wave height H_s and the peak period T_p are used in sediment transport studies. If these parameters were used to characterize the wave conditions, information about the structure of the spectrum would be lost. The use of the peak wave period would only represent sea, as the short wave components usually are predominant in the spectrum. Further, the calculated mean wave direction would not resemble the observed direction from neither the swell nor the sea waves, but instead some average angle, which does not represent the natural conditions. The littoral sediment transport is very sensitive to parameters such as the wave height, period and especially the wave direction. Small errors in these parameters may lead to considerable errors in the calculated sediment transport rates. The sediment transport mechanisms under swell waves are quite different from those under short period waves and thus care must be taken in the representation of complex sea states as in Pecém by these assumptions. Therefore, it is important to distinguish the swell from the sea and treat them separately in the sediment transport calculations.

In order to distinguish between sea and swell an analysis was made of the measured wave energy spectra. Each spectrum was subdivided in a discrete number of frequency intervals. For each interval a wave height was calculated according to the measured energy density in the respective interval. In this way, the wave energy spectrum was transformed to a number of individual wave events characterized by a wave height, period and direction. A statistical analysis was performed on all investigated spectra. From this analysis wave climates for each month of the year were derived. A dominance of sea is observed for the period from July to October. From December to April swell is dominant. The intermediate months show the occurrence of both wave types simultaneously. Fig. 4 shows the derived climates for January and July with a predominance of swell and sea respectively.

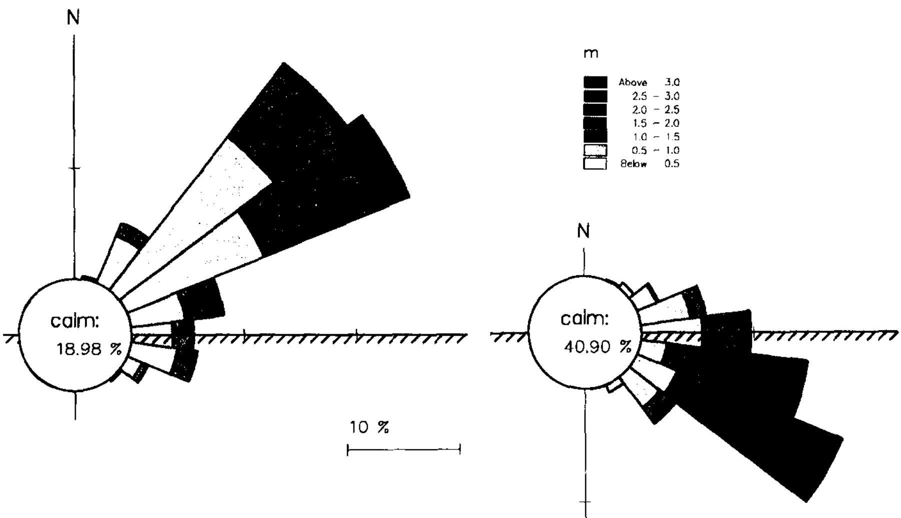

Fig. 4 Observed wave conditions at Pecém.
Left: January (Swell dominated) Right: July (sea dominated)

A number of characteristic wave conditions were simulated with a 2D wave model developed by DHI. The model is based on the parabolic approximation of the elliptic mild slope equations and includes dominant wave transformation phenomena such as refraction, shoaling, reflection, bottom friction and breaking. In these simulations, sea and swell were treated separately

Figs 5 shows simulated wave fields for an offshore wave height H_s of 1.75 m, a peak period of 7 s and a mean offshore wave direction of 82.5°. These wave conditions occur frequently in the area and contribute significantly to the net annual drift. Simulations for the present situation and the situation after establishment of the marine facilities are shown. East of Ponta do Pecém, the bathymetry is quite regular and the wave field is seen to be more or less uniform along this part of the coast. At the breaking point, the angle between the wave crests and the coastline is large, of the order of 45 degrees. This causes strong longshore currents that are able to transport large amounts of sediment along the coast.

At the western side of the headland, the wave field is rather complex due to the irregular bathymetry. The waves refract around the headland and approach the coast under a large angle. The area immediately W of Ponta do Pecém is sheltered by the headland. In front of the city of Pecém, wave breaking occurs far away from the beach due to the shoal that is located here. However, the shoal in front of the city does not provide much shelter for the incoming waves due to the large angles of incidence. Waves from these directions propagate between the headland and the shoal and reach the coast at Pecém under large angles.

The new harbor has a strong sheltering effect on the waves coming from easterly directions e.g. sea waves. The area of influence covers the entire area between the headland and the city of Pecém.

Fig. 6 shows the wave fields in the vicinity of Ponta do Pecém for swell. The convergence of the wave crests towards the headland is clearly seen. Immediately W of the headland, the coast is sheltered from wave action due to the headland. However, the shadow area is much smaller for swell waves than for sea waves.

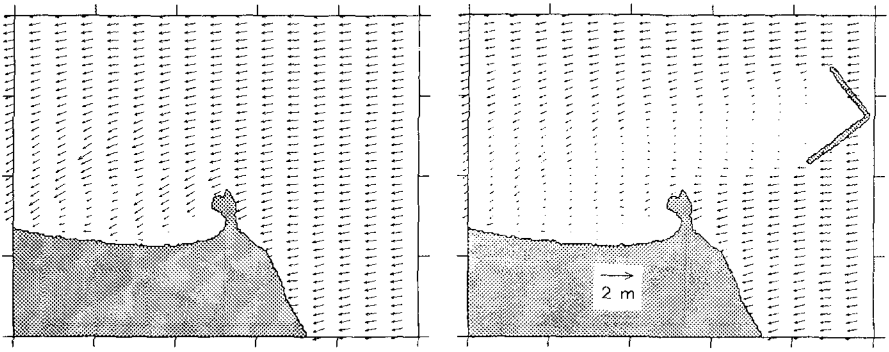

Fig. 5 Simulated wave field (Sea). Hs=1.75m, Tp=7s, MWD=82.5 °
Scale 1:70,000 Left: present situation, Right: including new harbor

The propagation of swell towards Pecém is not drastically affected by the harbor. Swell approaches the shore from offshore angles between approximately 20° to 45° N. The area where the sheltering by the harbor is maximal is located approximately 1.5 km E of Ponta do Pecém

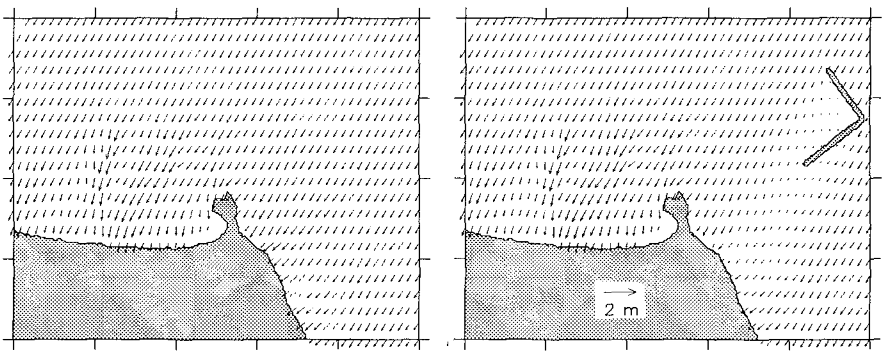

Fig. 6 *Simulated wave field (Swell). Hs=0.5m, Tp=14s, MWD=30°*
Scale 1:70,000 Left: present situation, Right: including new harbor

Nearshore hydrodynamics

In order to study the 2D wave driven currents, a number of hydrodynamic simulations were carried out with DHI's hydrodynamic model MIKE 21 HD. This is a general modeling system for the simulation of water levels and flows in estuaries, bays and coastal areas. The model solves the unsteady depth integrated flow equations. The driving force in the present simulations originates from the radiation stress field calculated with the wave model as described in the previous section.

The wave-driven current pattern for the present situation and after establishment of the harbor is shown in Fig. 7. Thc wave conditions correspond to sea (H_s = 1.75 m, T_p = 7s, MWD = 82.5° N).

The littoral currents are considerably stronger at the eastern side of Ponta do Pecém than on the western side. This is due to the more exposed character of the beaches on the eastern side. The littoral current follows the shoreline until it reaches the head of Ponta do Pecém. Close to the headland, the flow is slightly accelerating due to a local convergence of the depth contours. West of the headland, the current becomes detached from the shoreline. The flow velocities are highly reduced in this area. At a distance of approximately 1 km W of the headland, the current reattaches to the shore and its strength gradually increases towards W. Due to the irregular bathymetry in front of Pecém, complex nearshore current patterns can develop.

The presence of the harbor strongly reduces the littoral current velocities W of Ponta do Pecém. The harbor induces a large-scale eddy at the offshore edge of the headland. The littoral current becomes partly directed into the harbor basin, which may cause additional sedimentation problems inside the harbor.

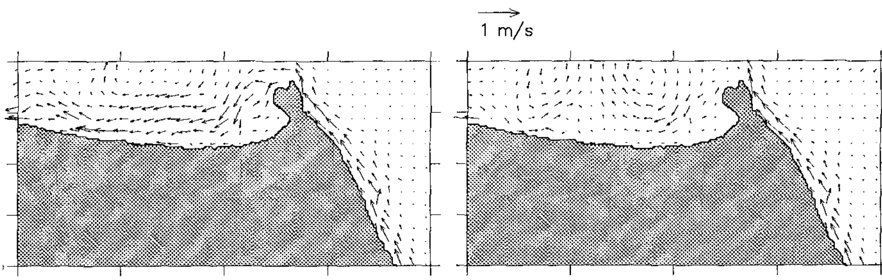

Fig. 7 *Wave driven current fields for the present situation (Sea). Offshore wave conditions: Hs = 1.75, Ts = 7s, MWD = 82.5° N Scale 1:55,000. Left: Present situation, Right: including new harbor*

Simulated wave driven flow fields due to swell are shown in Fig. 8. At both sides the currents are directed away from the headland.

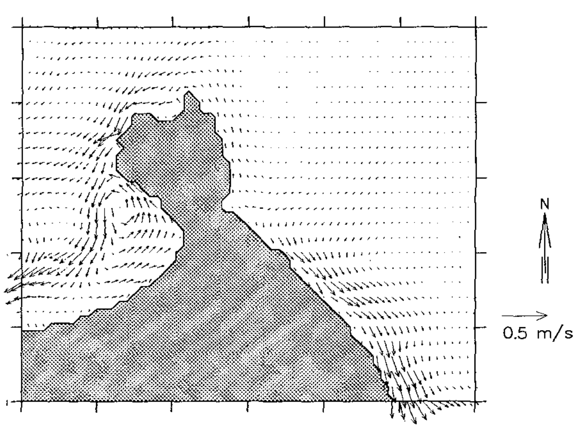

Fig. 8 *Wave driven current around the headland for the present situation (Swell). Scale 1:15,000. Offshore wave conditions: Hs=0.5m, Tp=14s, MWD=30°*

The flow velocities W of Ponta do Pecém are not significantly affected by the presence of the harbor. At the eastern side, the flow is slightly reduced due to the sheltering of the harbor. The maximal differences occur at a distance of approximately 1.5 km E of Ponta do Pecém.

Nearshore sediment transport

The complex sediment transport patterns for the present site were simulated with DHI's 2D sediment transport model MIKE 21 ST (Sand Transport). This model calculates the sediment transport of non-cohesive sediment due the combined action of currents and waves. Model calibration was performed upon available data of the Port of Mucuripe-CE, (see INPH 1986b). For a detailed description of sediment transport mechanisms in currents and waves, the reader is referred to Fredsøe and Deigaard (1992).

The results of the wave and current simulations were used as input for the sediment transport calculations.

During predominant sea relative large transport rates occur E of Ponta do Pecém. The harbor does not affect the littoral transport rates significantly in this area. Along this coastal stretch, at a distance of approximately 1 km E of the headland, the littoral transport is locally directed offshore.

At the western side of the headland, the littoral transport becomes detached from the shoreline. The sediment transport rates are reduced significantly for the new situation due to the decreased wave action and the associated strength of the wave driven current. The magnitude of the sediment transport is reduced considerably by the sheltering effect of the harbor on the nearshore hydrodynamic conditions in this area. With the presence of the harbor, the littoral transport at Ponta do Pecém continues further offshore than for the present situation without harbor and less, if any, sediment is passing Ponta do Pecém.

For swell waves, the littoral sediment transport pattern looks quite different. The coastline orientation in the area of Pecém varies from approximately 355 degrees N in front of the city to approximately 55 degrees N along the coastal stretch E of Ponta do Pecém. Due to this coastline configuration, the littoral current is directed towards E at the eastern side of the headland and towards W at the western side. The resulting littoral drift is therefore always directed away from Ponta do Pecém; towards E at the eastern side and towards W at the western side.

In this way, swell counteracts the sediment accumulations due to sea. East of Ponta do Pecém, swell reduces the net littoral transport rates towards the headland. On the western side of the headland, a part of the accumulated material is transported towards the shore by cross-shore transport mechanisms. Further towards West, swell gives rise to an additional westward drift.

During periods with prevailing swell, the spit developed during periods with predominant sea erodes. If the swell domination lasts for sufficiently long time, the coastline in front of Pecém erodes because the westward littoral drift due to combined sea and swell exceeds the sediment bypass around Ponta do Pecém, which is reduced due to the action of the swell.

Cross-shore sediment transport

In the calculations of littoral sediment transport the wave orbital motion was assumed described by one single wave with a constant height, period and direction. In case of longshore sediment transport this assumption is justified as the longshore transport is dominated by the longshore current and to lesser degree by the wave orbital motion, which is almost perpendicular to the coast in the surf zone.

However, the wave motion and the resulting shear stress are important for the calculation of the cross-shore sediment transport. The net cross-shore transport is determined by factors such as the strength of the undertow, the asymmetry of the wave orbital motion and the mass transport under progressive waves. In the present case the wave conditions are characterized by the simultaneous occurrence of sea and swell from different directions. In order to estimate the onshore sediment transport immediately W of the headland, an existing model for non-cohesive sediment transport was extended to include the effect of simultaneous occurrence of sea and swell. The basis for the model is DHI's sediment transport modeling system LITPACK. This model calculates the bedload and suspended load due to combined wave/current motion. The bedload is calculated from the sediment characteristics and the instantaneous bed shear stress, which was calculated from the solution of the turbulent wave boundary layer (Fredsøe 1984). The suspended load is calculated from the diffusion equation for suspended sediment (Fredsøe et al. 1985). Here the sediment exchange factor is taken equal to the eddy viscosity, which contains contributions of the wave boundary layer, the mean flow and the turbulence due to wave breaking (Deigaard et al 1986). The mean flow is calculated from the force balance across the water column (Deigaard 1993 and Elfrink et al 1996).

For the present application, the wave orbital motion was described by a linear superposition of a short wave component and a long wave component with different directions. Both components were assumed to occur as groups. The respective contributions to the total orbital velocity were calculated from 5^{th} order Stokes' or Cnoidal theory, depending on the local Ursell number. Fig. 9 shows an example of the wave orbital velocity composed of 2 wave groups with mean periods of 6 and 11 seconds. The angle between the short waves and the long waves was 60 degrees.

The orbital velocities were used to calculate the bottom boundary layer under the complex wave field. Fig. 10 shows the shear velocities, U_f, derived from the boundary layer solution

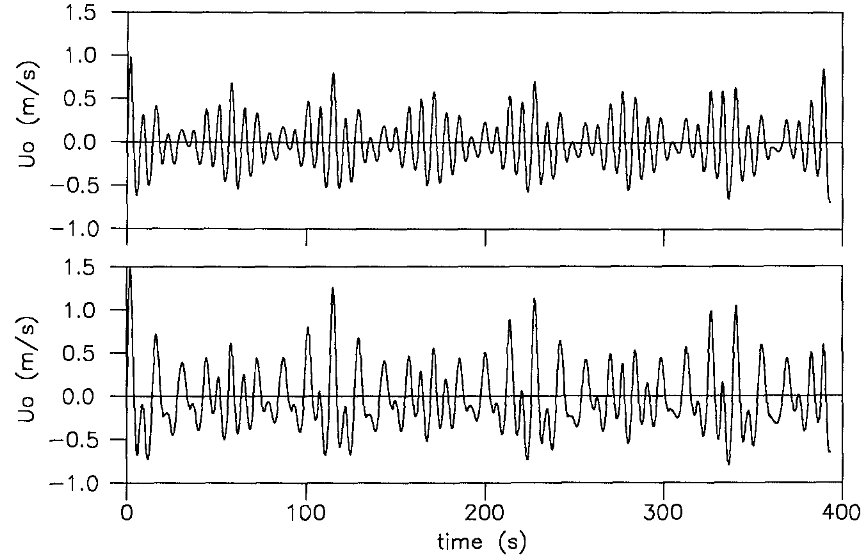

Fig. 9 *Instantaneous bed orbital velocities due to different wave groups. Top: Longshore component, Bottom: Cross-shore component*

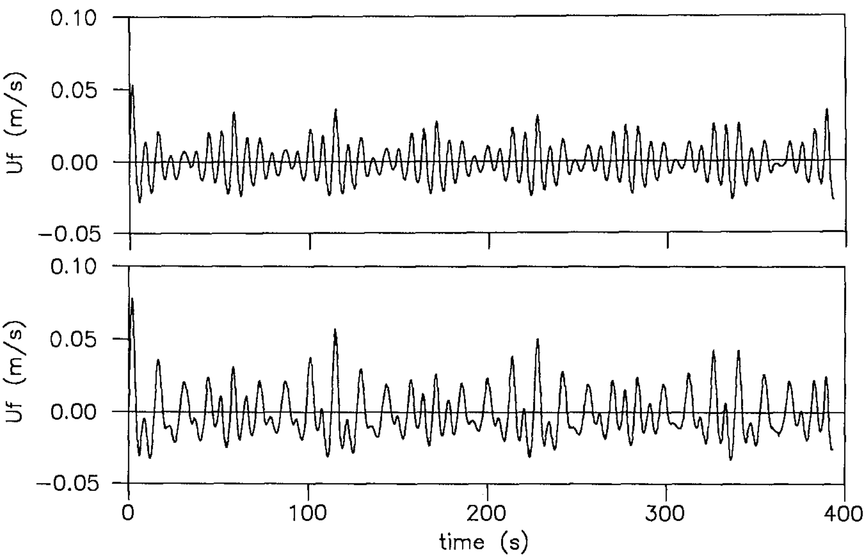

Fig. 10 *Instantaneous shear velocities due to different wave groups. Top: Longshore component, Bottom: Cross-shore component*

The resulting sediment flux, Q_t, in the cross-shore and longshore direction is shown in Fig.11.

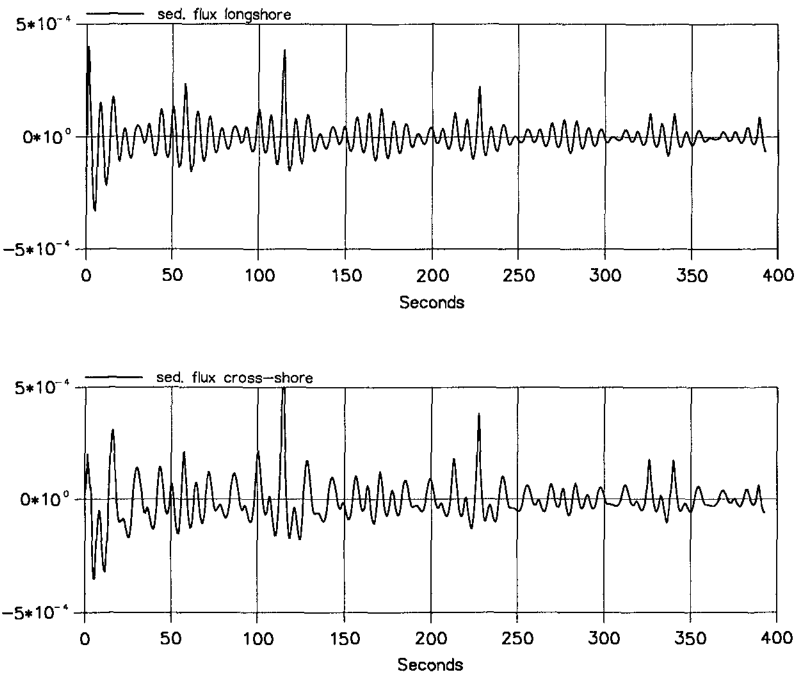

Fig. 11 *Instantaneous sediment flux due to different wave groups.*
Top: Longshore component, Bottom: Cross-shore component

The model was applied to estimate the onshore transport of sediment from the headland to the coastline W of it. It was found that the transport capacity under swell waves was increased due to the presence of short waves and vice versa. Even in cases were the two wave groups were taken perpendicular to each other.

The coastal sediment budget and future coastline evolution

The 2D simulations and the wave statistics were used to calculate the annual sediment balance.

Present situation

Along the beaches E of Ponta do Pecém a net littoral drift of the order of 350,000 m^3/year is transported towards W. The headland causes the littoral current to become detached from the shoreline. A total volume of approximately 90,000 m^3/year is transported offshore of Ponta do Pecém.

West of Ponta do Pecém, net onshore directed sediment transport occurs due to the reattachment of the littoral current and the net onshore sediment transport in (Non-breaking) swell waves.

West of the headland, the littoral transport is of the same order of magnitude as along the eastern side. The drift due to the sea waves is reduced due to the orientation of the beach and the sheltering of the headland. However, the importance of the drift due to the swell has increased, due to the larger angle between the swell waves and the coastline.

In the area immediately E of the city of Pecém, local gradients in the wave heights exist due to the irregular bathymetry. Here the littoral drift is reduced which gives rise to small accumulations. Further towards W, the littoral drift increases which causes erosion at the western edge of Pecém. This erosion/sedimentation pattern is confirmed by field observations.

Situation after establishment of the harbor

The main effect of the harbor is a strong reduction of the potential sediment transport rates due to sea waves in front of Ponta do Pecém and westwards, which results in increased sediment accumulations in front of and immediately W of the headland. A total sediment volume of the order of 115,000 m^3/year will initially accumulate in this area.

The flow velocities of the detached littoral current are strongly reduced due to the presence of the harbor. However, the transporting capacity of the swell is not affected in the immediate vicinity of the headland. A net onshore transport rate under swell waves of the order of 30,000 m^3/year was calculated. Approximately 85,000 m^3 sand will accumulate in front of Ponta do Pecém by means of a shore-connected spit.

Further West, the net littoral drift rates are reduced due to the sheltering of sea by the harbor. However, the combination of the reduced sediment supply and the reduced transport capacity of the littoral currents gives rise to erosion rates of the same order of magnitude, although slightly smaller, as for the present situation.

Further towards W, the effect of the harbor will vanish, which means that the littoral drift gradually increases from Pecém towards west. This leads to erosion between Pecém and Taiba.

From the calculated erosion/ sedimentation rates the annual coastline movements were estimated. East of Ponta do Pecém, the coastline is fairly stable. The accumulation of sediment due to the gradients in the littoral drift is of the same order of magnitude but slightly smaller than the net loss of sediment due to the wind. This gives rise to a slight coastline erosion of the order of 1 - 2 m/year. Variations occur during the year due to seasonal variations in the wave and wind conditions. The presence of the harbor does not affect the coastline dynamics in this area. However, in the long run the accumulations in front of the headland will change the coastline orientation in this area. This will cause coastal sedimentation. This coastline progress will start immediately E of the headland and proceed gradually in eastern direction.

After establishment of the harbor a shore-connected spit will start to develop from the headland. The spit will grow both in the offshore- and western direction. A part of the accumulated sediment will be transported by the action of swell. The total accumulation in the offshore region is of the order of 85,000 m^3/year. The presence of the spit itself will have an impact on the wave and current conditions along the beach W of Ponta do Pecém. Wave diffraction around the spit may cause a local divergence of the littoral current and the resulting sediment drift. This may lead to temporary coastline erosion immediately W of the projection of the spit on the coastline. This erosion process will proceed along the coastline as the spit develops. The erosion stops when the spit becomes attached to the coastline.

After establishment of the harbor the coastline erosion rates west of Ponta do Pecém, are of the same order of magnitude as for the present situation. A general coastline retreat of approximately 2 - 3 m/year must be expected due to the decrease of sediment bypass around ponta do Pecém.

Conclusions

A net annual littoral transport of the order of 350,000 m^3/year occurs along the entire coastline. Seasonal variations in the coastline position occur due to dominance of sea or swell during different periods of the year. Net erosion along the entire coast was observed.

Sea and swell have different effects on the net littoral sediment transport. Sea initiates strong littoral currents and relatively high transport rates along the coast E of Ponta do Pecém. Along the western side of the headland, the littoral drift is strongly reduced due to the sheltering provided by Ponta do Pecém and the different orientation of the coastline. The headland acts as a bottleneck for the littoral transport. This is of crucial importance for the stability of the coastline in front of the city. The topography of Ponta do Pecém forces the littoral current to become detached from the shoreline W of the headland. The sudden reduction in potential transport rates causes sediment accumulations around Ponta do Pecém.

The swell causes a sediment transport directed towards E at the eastern side of Ponta do Pecém and towards W at the western side. This transport pattern counteracts the accumulation of sediment around Ponta do Pecém due to sea. Sediment transport towards the shoreline occurs due to the sediment transport mechanisms associated with non-linear wave motion. During periods of predominant swell the sediment supply around the headland is strongly reduced. This causes beach erosion at the western side of Ponta do Pecém during the southern summer.

The main effect of the new harbor on the littoral transport is a general reduction of the potential sediment transport from Ponta do Pecém towards West. The littoral drift along the eastern side of the headland is initially not significantly affected by the harbor. The sediment bypass around Ponta do Pecém becomes heavily reduced. The reduced transport capacities W of Ponta do Pecém cause the development of a permanent shore-connected spit in the lee side of the headland. This accumulation will proceed in both northern (offshore) and western (longshore) directions. A net accumulation of the order of 85,000 m^3/year is estimated.

Further W of the headland the littoral drift will be reduced due the presence of the harbor. However, the gradients in the littoral drift along the shore are more or less the same as for the present situation. West of the city of Pecém, the sheltering effect of the harbor will vanish. This causes a gradual increase of the littoral drift rates between Pecém and Taiba and will give rise to increased coastal erosion in this area.

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