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Dynamics of a harbour littoral perimeter: the San-Pedro coast, South-west of Côte d'Ivoire

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Abstract:
The dynamics of San-Pedro harbour's perimeter was studied using 11 transverse profiles established behind the beach on 5 sites located between the Tombolo beach in the West and the Nautical Club beach in the East. Variable evolution of the coastal portion is observed, mainly related to the harbour structures and the variation of the hydrodynamic conditions. The morphological changes being the expression of the dynamic evolution obey to a seasonal rhythm which is characterized by an alternation of erosion periods from Mai to August and accretion between November and February. In addition, grain size analyses show a space variation of the average size, from Nautical Club to the Tombolo beach during the period spreading from 1985 to 1986, attesting the variable dynamics of the different beach portions.

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1. Introduction

Similar to the coastal countries of the world, the coastal landscapes of the Gulf of Guinea are facing the major environmental problems of natural or man-made origins of which coastal erosion is an illustration. The very significant rates of coastline retreat, under the hydrodynamic factors, are also related to the important maritime infrastructures built on some portions of the littoral, within the framework of countries economic development programmes (IBE, 1988; ROSSI, 1989; BLIVI, 1993; PASKOFF, 1993). In Côte d'Ivoire, the San-Pedro littoral perimeter, even considered globally stable (LE BOURDIEC, 1958; POMEL, 1979; KOFFI *et al*., 1989), is not free of this evolutionary tendency of the shore. San-Pedro was formerly a small village for fishermen installed along a river whose lower part forms a small estuary (photo 1). The development of this space after the construction of the harbour in the seventies generated a deep modification of the shores. This phenomenon seems to be exacerbated during the last few years, and the incidences disturb the initiatives for the development and modernization of the port which is the second economic lung of the country. The study of the air photographs collected between 1972 and 1993 (HAUHOUOT, 2000) allowed to follow the kinematics of the shoreline in this area. This study will raise some aspects characterizing the morpho-sedimentary evolution deriving from dynamics of the beach portions around the harbour’s infrastructures, observed respectively between 1985 and 1986 and between 1993 and 1997. The selected periods aim at confronting on one hand, during the same period and beyond that, the regular surveys on the ground and the previously indicated air photographs; on the other hand, to enhance the annual and multiannual characteristics of the sedimentary movements amplitudes, in order to better appreciate the space-time dynamics essential for the conservation of this space of high economic value.

2. Study area and methodology

2.1 <u>Study Area</u>

Located at the South-west of Côte d'Ivoire, the littoral of San-Pedro belongs to the littoral unit type of plates or dead cliffs coasts which dominate from 20 to 65 m a narrow littoral plain, located between Cape Palmas in Liberia in the West and Fresco in the East over approximately 250 km. This coast where sandy beaches and rocky capes alternate, also presents many creeks (Photo 2). The portion of coast concerned by this study spreads on approximately 5 km between the latitudes 4°43'21.35" and 4°44'48.17" North and longitudes 6°38'20.45" and 6°36'07.76" West. It covers the portions of beaches between the Tombolo and the lighthouse point.The survey of the changes on San-Pedro harbour’s littoral perimeter is carried out along 5 beach segments located on both sides of the harbour’s channel (figure 1).

2.2 Hydrodynamic characteristics

The littoral of Cote d’Ivoire is characterized by a semi-diurnal tide with low amplitude, ranging from 0.40 m in neap tides to 1.30 m in spring tides. The oceanic swell constitutes the main hydrodynamic factor responsible for the littoral sedimentary drift. It originates mainly from South-west to South-south-western sectors, with amplitudes spreading from 1.0 to 2.0 m and a period of 10 to 11 seconds. Analysis of the monthly frequency (table 1) of various swells shows an all year round average swell. June, May and July are characterized by a strong swell, while, November to February are affected by weak swells. The lack of more accurate and recent statistics is due to the absence of continuous swell records. Authors agreed on the existence of a littoral drift oriented from West to East with quantities of mobilized sediments of about 200000 m^3/year in San-Pedro and 800000 to 400000 m^3/year in the Abidjan area, respectively in Vridi and Port-Bouët (TASTET *et al*., 1985).

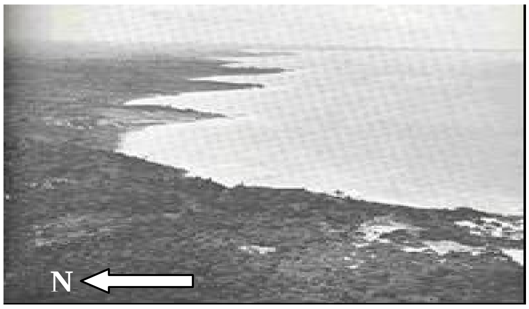
Table 1. Monthly frequency (%) of different swells (LE BOURDIEC, 1958).

Month	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
Weak swell *(amplitude lower than 0.8 metre)*	*45*	*28*	*18*	*24*	*12*	*06*	*17*	*36*	*45*	*34*	*51*	*58*
Medium swell *(amplitude ranging between 0.8 and 2 metres)*	*45*	*62*	*59*	*53*	*42*	*53*	*55*	*48*	*41*	*59*	*44*	*37*
Strong swell *(amplitude higher than 2 metres)*	*10*	*10*	*23*	*23*	*46*	*41*	*28*	*16*	*14*	*13*	*05*	*05*

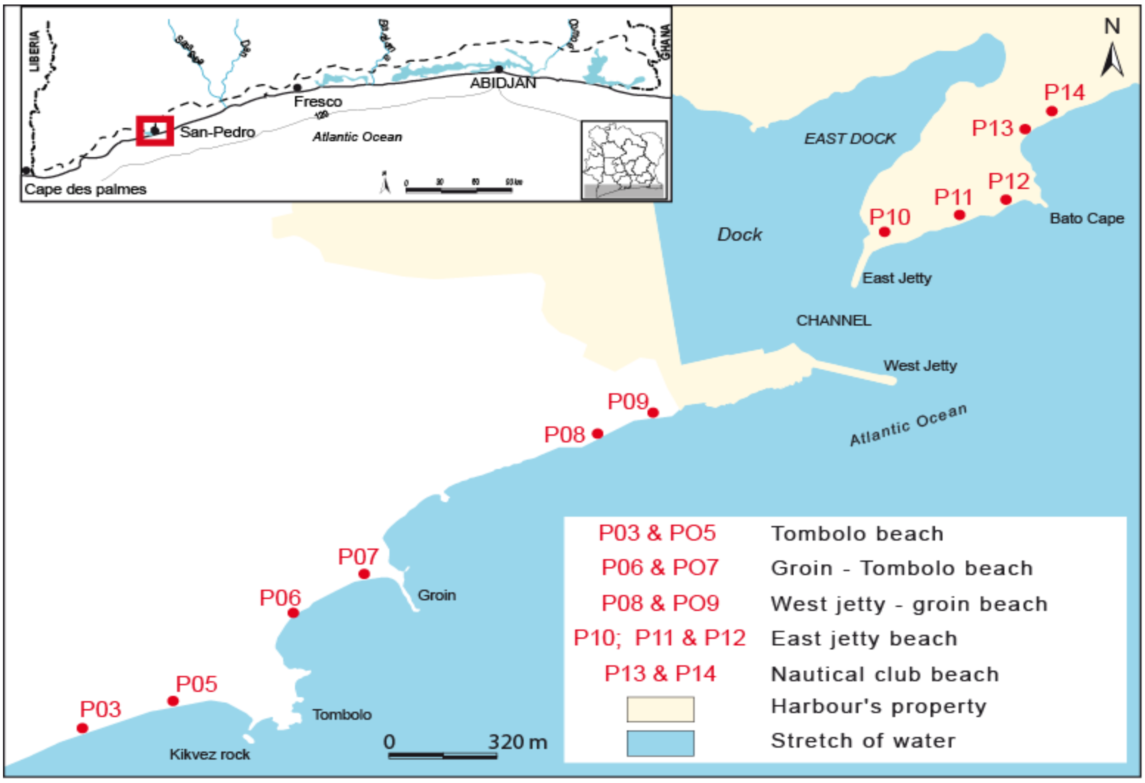
2.3 Study Method

In collaboration with the Hydrographical Department of the San-Pedro Port authority, several beach profiling surveys and simultaneous sediment sampling were carried out on the study area. This morphological and sedimentological investigation of the evolution of beach portions, using topographic equipment (IBE & QUENNELEC, 1989), tacheometer Wild RDS type, is conducted on a network of 14 topographic profiles linked to reference benchmarks, judiciously distributed on the beach portions of the harbour area and beyond, bordering the port infrastructures and rocky headlands. In order to evaluate the evolution of the various beach portions in relation with the infrastructures and the natural hydrodynamic characteristics, 11 profiles covering the 5 beach portions (figure 1) were used during this survey. The sediments were analyzed according to the technique described by SAAIDI (1991) on a column of 16 sieves (AFNOR series) and were characterized by the mean grain size (Mz) and the classification index (σ) obtained from FOLK & WARD (1957).

Photograph 1. Natural inlet of the San Pedro river in 1967 (RCI, 1980).



Photograph 2. Coast in levels in the South-west of Côte d'ivoire (air discovery of Côte.d'ivoire, 1974).



Source : Fond de carte PASP, juin 2009

Figure 1. The study area.

North-South transverse topographical surveys and the sedimentological data are compared following a variable scale of time corresponding to seasons and years, quantities of mobilized sediments are then estimated by determination of eroded or accreted surface areas (BRABANT, 2003).

3. Results

Topographic and sedimentological data acquisitions were carried out around low tide of the moment, and same way during the survey periods.

3.1 Morpho-sedimentary trend between 1985 and 1986

3.1.1 Portions of beach in the Eastern side of the harbour channel (Beaches at Nautical Club and East Jetty)

Morpho-sedimentary dynamics in the East of the harbour channel shows an intense regressive evolution at the level of the Club Nautique beach (P14 and P13). This area is affected by the interruption of the West-east littoral drift, but also because of the configuration of the coast and the prevailing wave energy. During the 1985-1986 period occurred a remarkable movement with an average rate of coastal retreat of more than 5 m/year which seems to be accelerated by the storm occurring before May 23, 1986. This phenomenon is expressed by a spasmodic shoreline retreat of 4 m and a considerable reduction the beach width. The profiles develop significant erosion slopes with an unevenness of more than 3 m (figure 2). The beach portion at East Jetty (P12, P11 and P10) shows, during the same period, a relative stability of the coastline, except for profile 11 (central profile) which undergoes an evolution similar to the preceding beach portion, with an average retreat of more than 2.5 m/year and a slope unevenness of less than 1.5 m (figure 3). Notwithstanding the storm of May 1986, the beach profiles essentially show seasonal readjustments conferring them an annual dynamic balance on this portion. The amplitude of the seasonal sedimentary movements under the influence of the storm of May 1986 in the East of the harbour channel remains globally significant. It varies between 1 and 3 m.

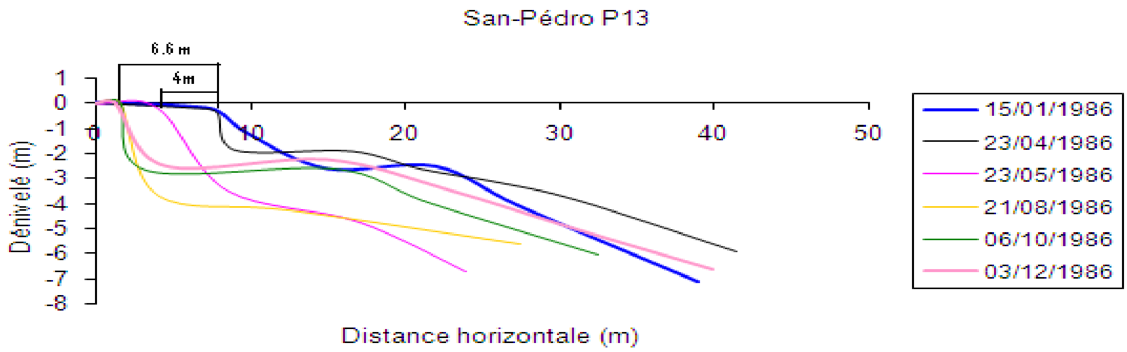


Figure 2. Morphological evolution of profile 13, Nautical Club sector, in 1986.

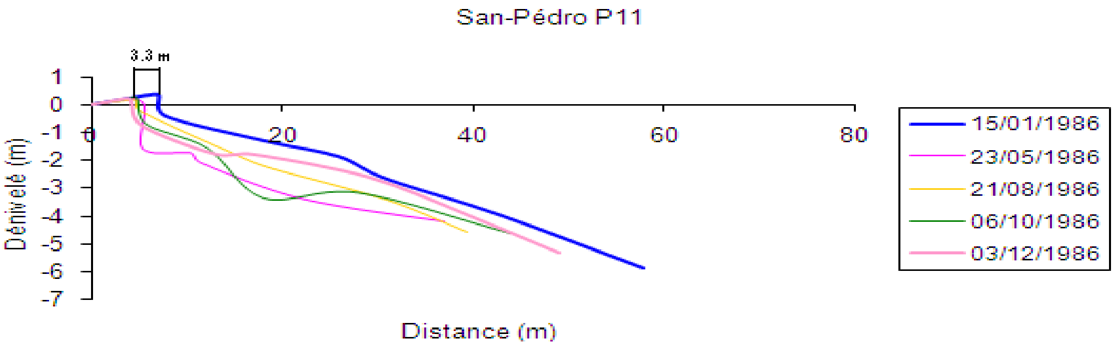


Figure 3. Morphological evolution of profile 11, East Jetty sector, in 1986.

3.1.2 Portions of beach in the West of the harbour channel (beaches West Jetty-Groin, Groin-Tombolo and Tombolo)

Morpho-sedimentary dynamics in the Western side of the harbour channel, during 1985-1986 period, allow to distinguish three beach portions with non homogeneous dynamic. It is characterized by the alternation of stable, eroded and accreted zones. Therefore, the beach located between the Western Jetty and the groin is stable. The dynamic variation of beach profiles in this zone reflects the geomorphology and the type of substrate on which they are established. Thus, erosion and accretion between mid and low beach alternate during agitated time and good weather periods. At the tombolo the beach is essentially accreting, shown by generally convex profiles (figures 4 and 5), it results from trapping of the sediments of the West-east transfer by the transverse rock blocks. The situation is different in the portions of beach located between the experimental groin and the tombolo where, on the immediate downstream of this structure, the rate of coastal retreat is high reaching in average more than 5 m/year (figure 6) due to the interruption of the transfer of sediments towards the harbour's channel. This dynamics, although spectacular, seems to be influenced by the storm which has occurred in May 1986. The amplitude of the vertical movements remains low. It hardly exceeds 1.7 m.

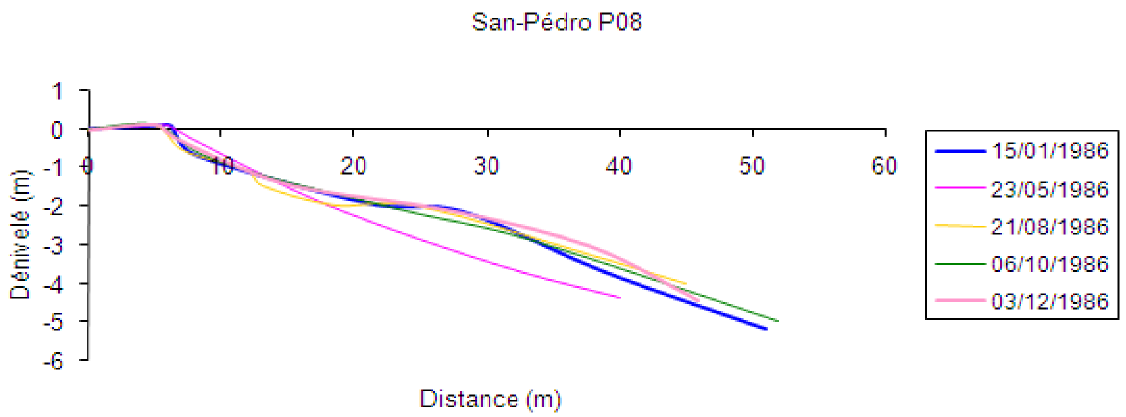


Figure 4. Morphological evolution of profile 08, sector West Jetty-Groin, in 1986.

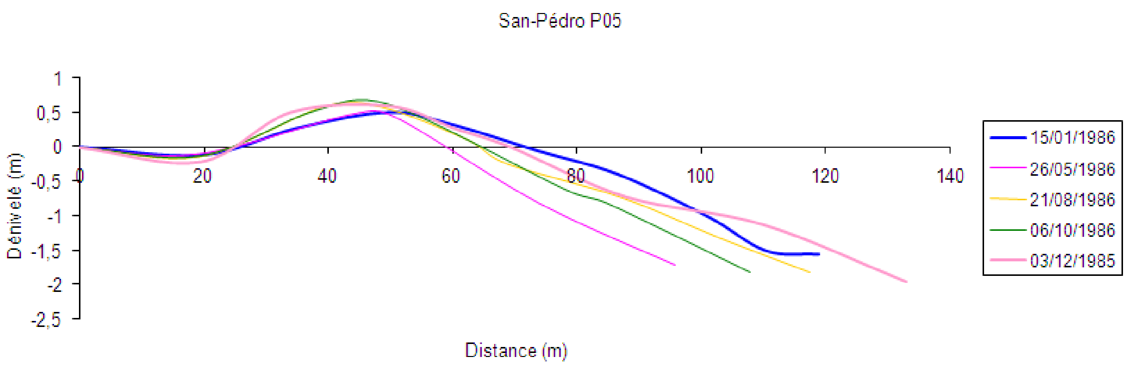


Figure 5. Morphological evolution of profile 05, Tombolo sector, in 1986.

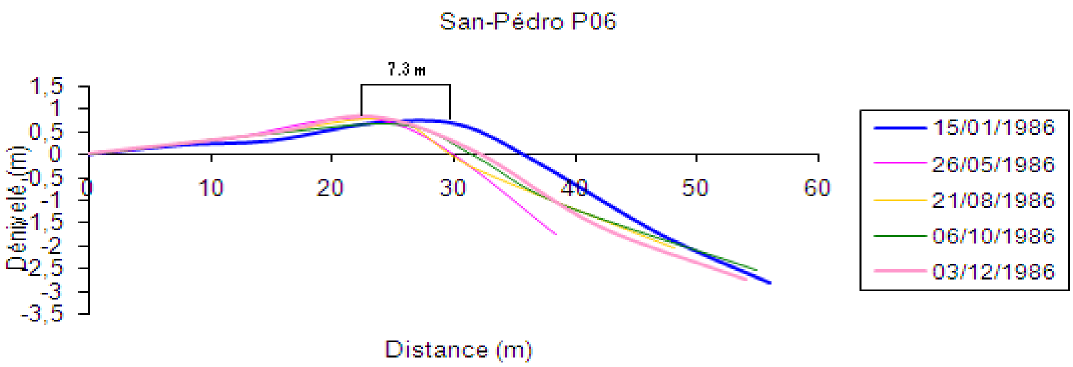


Figure 6. Morphological evolution of profile 06, Groin-Tombolo sector, in 1986.

3.2 Morpho-sedimentary evolution between 1993 and 1997

3.2.1 Portions of beach in the East of the harbour channel (Beaches at Nautical Club and East Jetty)

The beach segments in the Rast of the harbour's channel record mean velocities of retreat of the shoreline of about 1.2 m/year during the period 1993-1997 (figure 7 and 8). The regular setting of new bench marks during the survey period, testifies to the importance of the retreat process at the Nautical Club, facing the profile 14. Thus, the swing of the coastline inland generated a widening of the upper beach. The picture is different on profile 13; the multiannual vertical movements tend to balance on the level of the beach. On the East Jetty portion of beach, the mean velocities of shoreline retreat attenuate from West to East, in opposite direction of the importance of the envelope of the vertical sedimentary movements. Levels of erosion slopes are significant (approximately 1.5 m) but remain largely lower than those recorded during the period 1985-1986.

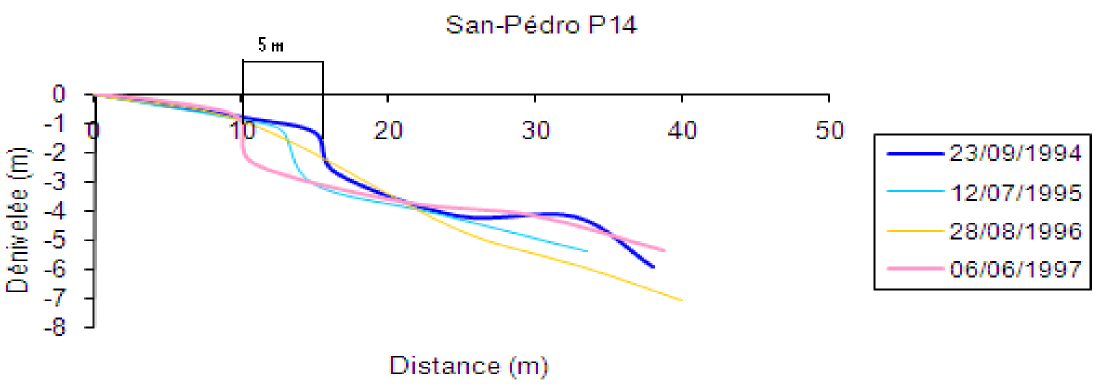


Figure 7. Morphological evolution of the profile 14, Nautical Club sector, between 1993 and 1997.

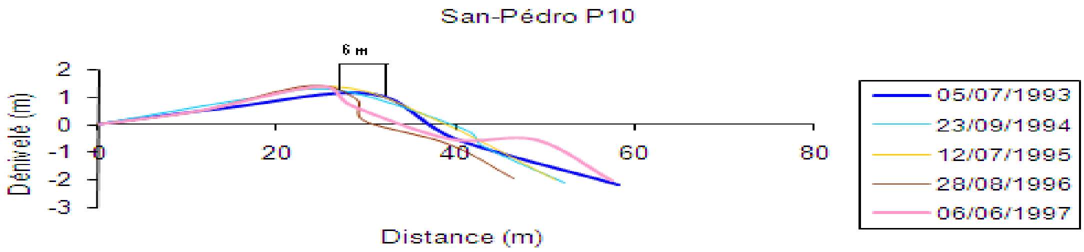


Figure 8. Morphological evolution of profile 10, East Jetty sector (1993 to 1997).

3.2.2 Portions of beach in the West of the harbour channel (West Jetty-Groin, Groin-Tombolo and Tombolo beaches)

Changes of the beach segments in the West of the harbour channel between 1993 and 1997 are almost identical to the ones defined during the period 1985-1986. Apart from the west jetty-groin beach segment which is stable, the beach at Tombolo shows a remarkable accretion during the surveyed period which testifies to the deterioration of the longitudinal sediment transport by the harbour's protection structure. The location of the break in the slope moves gradually from 165 m to 222 m, then from 122 m to 164 m respectively on profiles 3 and 5 (figure 9). Conversely, the next sector groin-Tombolo, undergoes a considerable nonlinear erosion with a mean velocity of retreat of the shore of about 1.6 m/year, near the Tombolo beach (figure 10). In general, the dynamics of the beach segments on both sides of the harbour channel and protection structures are similar to the ones observed at Port-Bouët (East of the Abidjan harbour) on the sandy littoral (TASTET, 1987), as well as elsewhere in the Gulf of Benin (IBE 1988; BLIVI, 1993).

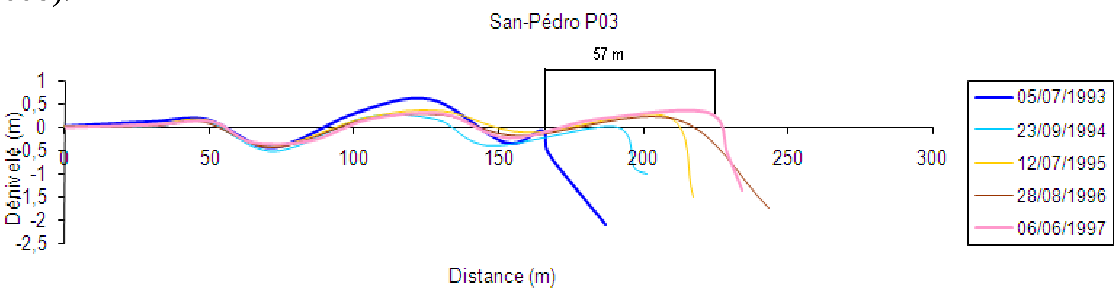


Figure 9. Morphological evolution of profile 03, Tombolo sector (1993 to 1997).

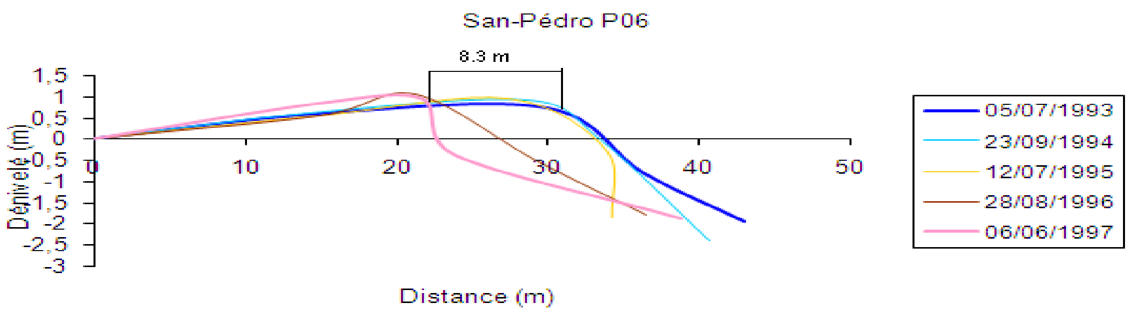


Figure 10. Morphological evolution of profile 06, sector Groin-Tombolo, between 1993 and 1997.

3.3 Beach sediment characteristics and volumetric assessment

Beach sands are characterized by various parameters of which the mean size and the classification. The evolution of this mean size during 1985-1986 reveals a space grain size variation. Whatever the period is (storm surge from May to July and lull from November to February) grain sizes of the sediments at San-Pedro beach vary from coarse to mean sands from the nautical club to the East of the harbour channel to the groin located on the West side of the aforesaid channel, with mean sizes ranging between 0.35 mm and 0.73mm. From the groin to the tombolo, sands are medium to fine. The granulometric averages oscillate between 0.12 mm and 0.43 mm. Sands in general are moderately classified and heterogeneous apart from the sector of Tombolo beach where sands are homogeneous. This change of the granulometry from East towards West have also been observed by HAUHOUOT (2000), it reflects not only the imbalance of the beach but also a variation of the importance of the dynamics from the energy point of view (NIANG- DIOP, 1995; PINOT, 1998). The quantities of sediments mobilized on the beach follow the dynamic trends of the various beach segments (table 2).

Table2. Volumetric quantification of sediments mobilized on the shore

Beach segments	*Volume of sands mobilized between 1985-1986 (m^3)*	*Volume of sands mobilized between 1993-1997 (m^3)*	*Dynamics Trend*
Nautical Club	*- 7 438*	*- 1 497*	*Erosion*
East Jetty	*- 3 257*	*- 2 094*	*Erosion*
West Jetty-Groin	*- 1 069*	*- 2 553*	*Erosion*
Groin-Tombolo	*- 3 495*	*- 4 600*	*Erosion*
Tombolo	*+ 4 213*	*+ 32 317*	*Accretion*

4. Discussion

This study combines an *in situ* inspection of the natural environment with a reflection on the nature of the aforesaid area and its hydrodynamic conditions. Based on the existing data it would be difficult to show with certainty the natural evolution of the urban San-Pedro coastline before the construction of the port, and to measure efficiently the consequences of harbour installations on the current evolution of the shore. The shoreline in a large scale would be relatively stable with an imbalance (accretion upstream of a cape and erosion downstream) in the neighbourhood of mini rocky capes due to littoral drift. The morphological analysis of the dynamic evolution of the San-Pedro littoral allows to establish the destabilization of the portions of coast where harbour installations and exceptional events, such as storm, seem to have had a strong influence. In fact, the morphological observations reveal important speeds of retreat (1.2 to 1.6 m/year on average between 1993 and 1997), exacerbated by the storm

(approximately 5 m/year on average between 1985 and 1986), immediatelly downstream of the trapping sediment structures of the West-East drift. Contrarily the upstream beach sector shows a remarkable advance of the shore (8 to 11 m/year on average between 1993 and 1997). These results corroborate the evolutionary tendencies demonstrated by HAUHOUOT (2000) in this area. The speeds considered although variable according to the data sources and the extent of the study periods always shows the strong degradation of the beach portions downstream of harbour infrastructures. This dynamic evolution reflects work results from KIRK (1992), DIBAJNIA et al., (2004) according to which, the interruption of the longitudinal transport of the sediments by the presence of coastal infrastructures causes an extension of the beaches located at the wind as well as the erosion of the littoral located under the wind. PASKOFF (1993) also underlines that the harbour installations which advance towards the open sea seriously disturb the movement of materials conveyed by the littoral drift. They modify the behaviour of the adjacent shores. Alluvial deposits are formed against jetties which stop the trend while the portions located beyond these obstacles thin down and move back because of lack of sedimentary contribution. In addition to the harbour zone of San-Pedro, the profound change of the evolution of the shores after the construction of the Abidjan harbour, on the low Ivorian sandy coast illustrates perfectly this reflection (TASTET, 1987; ABE & BAKAYOKO, 1995). In addition, IBE (1988) and BLIVI (1993) also point out that in Lomé, Togo and in Cotonou, Bénin, some beaches located at the East of the ports, deprived of sedimentary contributions, recorded a considerable retreat up to respectively 20 to 24 m/year and 50 m/year.
The morphology of the profiles answering faster to environmental modifications such as sediments (NIANG-DIOP, 1995), allowed SHERMAN (1991) to deduce their characteristics and also the local wave energy regime. These characteristics, in granulometric terms, show a space variability which refers the dynamics of the various beach portions.
The results of the sedimentological analysis are also similar to those of ABE (2005) except for the beach Tombolo which shows fine and homogeneous sediments. Sequel to the preceding, it is advisable to note that harbour installations and exceptional storms are the most significant factors destabilizing the coasts.

5. Conclusion

The analysis of the topographical and sedimentological surveys in the vicinities of San-Pedro harbour’s was carried out to better understand the sediment dynamics of the coast near the harbour’s infrastructures. The morpho-sedimentary evolution of the studied area opposes clearly the beach portions between Nautical Club, East Jetty and Groin-Tombolo with the sector of Tombolo beach. The mean velocities of shoreline retreat of about 5 m/y between 1985 and 1986 in the immediate East of the structures trapping sediments would be reinforced by the storm which has occurred in May 1986. These speeds attenuate during the period of 1993 to 1997, and indicate an average retreat of about 1.2 to 1.6 m/ year. On the other hand, the tombolo area reveals a spectacular progression of approximately 8 m/ year. The synchronous granulometric studies reveal a space variation of the sediments grain size, corollary of the dynamics of the various beach portions. It thus appears significant to stress that this considerable and localised regressive dynamics contrasts with the development plans under consideration by the Port authorities in the East of the channel. These prospects amongst other things relate to the construction of 700 m of quay, of 10 to 25 ha of ground fill intended respectively for the installation of a park for containers and of an oil terminal on the littoral separating the sea from the East dock of the port. Moreover, the dynamics of the Tombolo beach (located beyond the limit of the harbour field) in a longer term seems to pose the problem of its saturation and thus of its dysfunctioning in its role of sediments trap. The development of a sustainable management plan, for research and decision-making purposes thus proves necessary, in order to safeguard this coastal environment of cardinal importance. Also, the proposal for a sedimentological model analysis as tool of prediction of the morpho-dynamics and coastline evolutions would be welcome. Such a study under consideration by the General - Directorateof the San-Pedro harbour would allow more accurate assessment of the performance of the structures protecting the port constructed along the coast, as well as the trend of future changes.

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