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Flood Management in Saint-louis City of Senegal by Stabilizing the Breach

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Abstract In October 2003, the city of Saint-Louis, a UNESCO World Heritage Site, was to be swallowed by the rising waters of the Senegal River. That is why, the public authorities and the communal authorities wanting to find an immediate solution to save the city and human lives, took the decision to create a channel of load shedding on the Barbary language called breach. This urgent political decision seems to have profoundly modified the hydrological behavior of the Senegal River in Saint-Louis. The breach opened in Saint-Louis to counter the flood phenomenon, has since the night of October 3 to 4, 2003, the date of its opening, caused many environmental problems resulting from profound changes in the biophysical characteristics of the area (floods, loss of biodiversity). However, many specialists are still thinking about the issue but still do not find sustainable solutions to restore the balance. The aim of this study is to propose technics for stabilizing the area with two specific objectives such as understanding its evolution and evaluating the threats to the neighbouring villages. This study on the evolution of the breach from 2003 to 2013 is based is conducted by analysis of samples taken from the Langue de Barbarie and the breach to determine their type. The main results show that the soil is sandy, which has made it possible to propose structural and non-structural stabilization methods. The compilation of the different results shows two types of stabilization (structural methods and non-structural methods). The two methods constitute for each of them, a durable alternative solution for the stabilization of the breach in order to limit the environmental damages. Meanwhile, it would be important to monitor the structure by annual analyzes of the structure.

Keywords: *Saint-louis, flood, breach, environment, structural methods, non structural methods*

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1. Introduction

Senegal is widely open to the Atlantic Ocean with coasts extending over 700 km and often is facing serious coastal erosion, aggravated by the digging in 2002 of an artificial discharge of the river Senegal just south of the city of Saint-Louis [1]. Its climate is of Sahelian type characterized by a warm and rainy season, marked by the circulation of the monsoon from June to October and a dry season during which blow the continental trade winds predominantly N-NW [2]. Its coast occupies an important place in the economy of the country because of the diversity of economic activities such as fishing, tourism, agriculture, industry and transport. However, the durability of these activities is threatened because of the degradation of the natural environment reinforced by man's action (construction of port or tourist infrastructures, the creation of artificial mouths). These practices combined with a high rainfall are causing major floods in the delta front of the Senegal River. It is in this context that the Senegalese public authorities have particularly decided to open an artificial channel called a watershed or breach to save the city of Saint-Louis from flooding. The main reason for this breach was related to the city of Saint-Louis [3].

The city of Saint-Louis, located in the estuarine area, undergoes more and more frequent floods, the largest of which is recorded with a peak in 2003 [4]. In October 2003, following an accumulation of flood surges on the river and the complete opening of the floodgates at the Diama dam, all the lower areas of Saint-Louis were flooded or threatened [4]. The water level was at the 1.94 m coast in the night of October 3 to 4, 2003, for a warning threshold of 1.75 m. During that time, the water pressure was such that there was fear of a natural opening of a breach at the north of the Goxxumbacc district, which justified the opening of a breach at 7 km south of the neighborhoods built on the Langue de Barbarie [5].

The breach, also called "canal de délestage" by the authorities of the city was opened to allow a faster evacuation of the river waters towards the sea before they invade the city of Saint-Louis. This development was to reduce by approximately 40% the flooded areas around Saint-Louis [4].

Although modest at first, its consequences are considerable because being in a fragile estuarine mid-place and very exposed to the fluctuations of the tide and the coastal erosion. Indeed, this opening, made in the emergency without a dike allowing its stability, has become the new mouth of the river. It has been growing since its opening because of the combined action of the swells and the river waters that flow into the sea. Thus, notwithstanding its very important role in the flood management waves during the winter period, this breach causes periodically many inconveniences to the populations and produces a socio-ecological modification of environment of the area. The river and its tributaries are gradually filling in, the watercourses are getting smaller with a plug effect amplified by the continuous silting of the major bed of the river. The flow conditions are reduced and the protective dikes along the river crumbled, causing breaches, which favor the infiltration of water to the localities of the valley and the Delta, between Matam and Saint-Louis.

The high flood recorded in September 2003 (228.6 mm) explains the flood at that time and the real threat to the city of Saint-Louis. This phenomenon caused the people's fear and the government's hasty decision to open a channel known as a breach or relief canal to fight against these floods.

This urgent political decision seems to have profoundly modified the hydrological behavior of the Saint-Louis River [6]. Since that date, the colonial city has not been flooded [7,8,9,10]. However, it is questionable whether the risk of flooding has been ruled out in the medium term. The gap has indeed widened dramatically [1,8,9,11,12]. The result is a strengthening of marine influences in the operation of the St. Louis River, which results in particular in a modification of the tidal range. This point has been emphasized in two previous studies [7,8]. However, this work leaves open the question of the impact of this modification of the hydrological regime of the river on the medium-term sensitivity of the city to marine submersion hazard. Today, there is a fairly broad consensus within the scientific community to estimate that a sea level rise in the 21st century is likely [12].

The aim of this study is to propose structural and non-structural bridging stabilization techniques for water and environmental management.

2. Study Area

The coastal region of Saint-Louis is located in northern Senegal at the meeting point between the river and the Atlantic Ocean. It opens on the latter for nearly 25 km from the district of Goxoumbacc to the village of Taré, area of our study (Figure 1). Its coordinates are 16°02 'North for latitude and 16°30' West for longitude. The floods of Senegal have marked the history of the city of Saint-Louis since its creation by French settlers in the seventeenth century north of the mouth of the river [6,13,14]. Nine major floods that caused flooding in the colonial city are recorded in the nineteenth century (1827, 1841, 1843, 1854, 1855, 1858, 1866, 1871, 1890) and 9 in the twentieth century (1906, 1922, 1924, 1935, 1950, 1994, 1997, 1998, 1999) [15]. The topography of Saint Louis city is low with altitudes relative to the hydrographic level between -1.82 and 7.14 m.

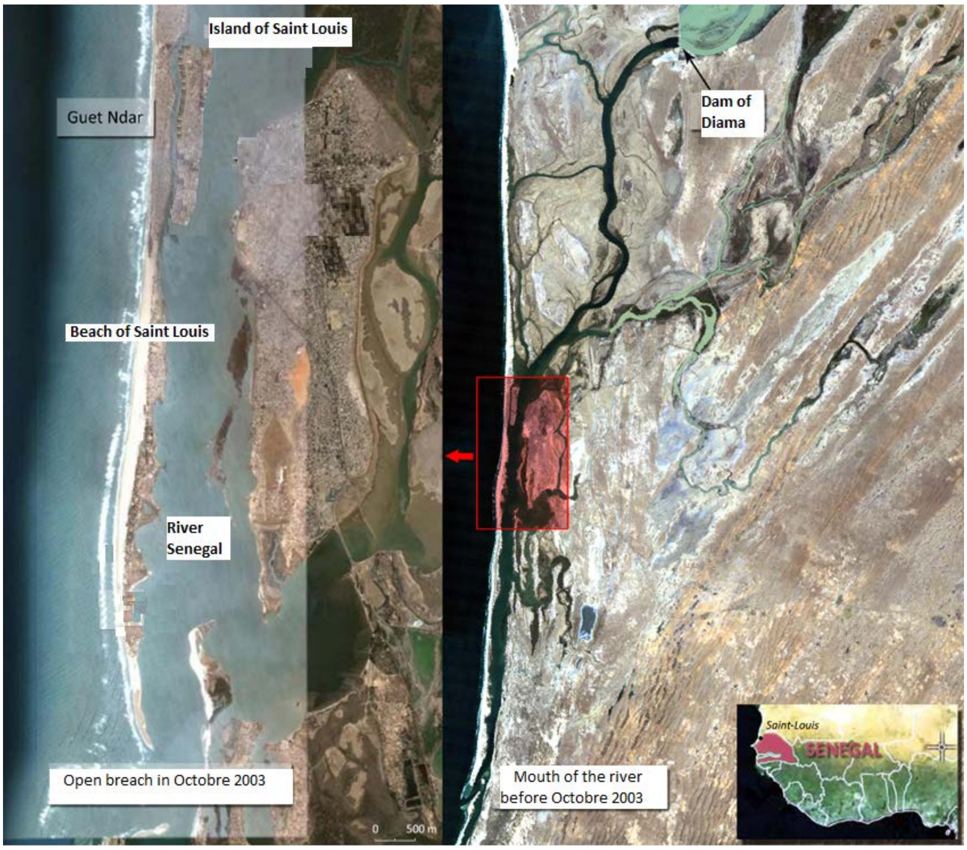

Figure 1. Location of the city of Saint Louis [15]

However, that city belongs to the Sahel region, which is made up of "a group of African countries bordering the southern Sahara, countries which are not desert but where rainfalls are relatively small (< 600 mm), irregular, distributed over a single area. A wet season followed by a dry season that lasts for long months and during which it hardly falls a single drop of water [5].

Downstream of the Diama Dam, the river system consists of backwaters, Djeuss stopped downstream of Dakar-Bango, small tributaries such as Khor and Marmeal which cross the river upstream of Gandiole. In the city, the large river Arm crossed by the Faidherbe bridge separates the continent from the island and to its western part, the small arm which connects it to the Langue de Barbarie, sandy arrow where the mouth of the Senegal River is located. In the South of the city there is a lagoonal complex between St. Louis and Gandiole. The island of Ndar is connected to the Langue de Barbarie by two bridges, one in the north and one in the south. It extends from north to south over 2.5 km and a width of 350 m. Two large districts meet Lodo in the north and Sindoné in the south. It is stuck between the two arms of the river.

The mainland of the island town is constituted by the suburb of Sor. This area includes more than 60% of the population of Saint-Louis. It consists of two nuclei; one of traditional occupation (Tendjiguène, Balacoss...) and the other occupation more recent between 1960 and 1970 whose main districts are Pikine, Darou, Medina ... These neighborhoods are built on saltlicks and some occupy part of the most flood-prone areas of the river.

The Hydrodynamic waters of Saint-Louis is characterized by the main currents, the cold current of the Canaries and the equatorial warm countercurrent [18], swells and waves, and water masses [19].

The climatic conditions show a Sahelian zone with a climate characterized by a hot and rainy season, and a dry season during which the continental trade winds blow [16].

The monthly rainfall of the Senegal River reaches a maximum during the year between July and September (Table 1) (Figure 2) [17].

Table 1. Rainfall in Saint Louis: Cumulative monthly in mm from 1993 to 2013 [19]

Stations	Years	January	February	March	April	May	June	July	August	September	October	November	December
Saint-Louis	1993	0	0	0	0	0	0	**7,0**	**126,8**	**103,6**	**0,2**	**1,2**	0
Saint-Louis	1994	0	0	0	0	0	0	**7,4**	**64,1**	**192,3**	**20,5**	0	0
Saint-Louis	1995	0	**3,3**	0	0	0	**2,5**	**37,6**	**101,5**	**125,9**	**11,2**	0	0
Saint-Louis	1996	0	0	**1,1**	0	0	**11,4**	**19,3**	**46,6**	**16,6**	**15,8**	0	0
Saint-Louis	1997	0	0	0	0	**3,2**	**8,7**	**0,1**	**146,2**	**62,0**	0	0	0
Saint-Louis	1998	0	1	0	0	0	0	**2,0**	**134,4**	**132,1**	**3,5**	0	0
Saint-Louis	1999	0	0	0	0	0	0	**53,6**	**146,6**	**33,3**	**128,1**	0	0
Saint-Louis	2000	0	0	0	0	0	0	**168,5**	**49,5**	**68,4**	**42,9**	0	0
Saint-Louis	2001	0	0	0	0	0	0	**36,7**	**107,3**	**92,8**	**19,1**	0	0
Saint-Louis	2002	**66,2**	0	0	0	0	**10,9**	**32,0**	**28,0**	**35,9**	**88,8**	0	0
Saint-Louis	2003	0	0	0	**1,7**	0	0	**9,9**	**47,3**	**228,6**	**62,3**	0	0
Saint-Louis	2004	0	**1,8**	0	0	**0,1**	**0,2**	**8,7**	**94,8**	**34,1**	0	0	0
Saint-Louis	2005	0	**2,0**	0	0	0	**22,7**	**147,1**	**69,3**	**38,5**	**0,4**	**1,5**	0
Saint-Louis	2006	0	**1,2**	0	0	0	**13,8**	**114,5**	**90,9**	**70,3**	**3,9**	0	0
Saint-Louis	2007	0	0	0	0	0	0	**10,1**	**140,0**	**160,6**	0	0	0
Saint-Louis	2008	0	**10,0**	0	0	0	**7,8**	**67,1**	**79,6**	**91,1**	**1,4**	0	0
Saint-Louis	2009	0	**1,2**	0	0	0	**13,8**	**114,5**	**90,9**	**70,3**	**3,9**	0	0
Saint-Louis	2010	0	0	0	0	0	**27,9**	**70,4**	**65,9**	**320,1**	**109,3**	0	0
Saint-Louis	2011	0	0	0	0	0	0	**49,2**	**107,7**	**115,8**	**4,1**	0	0
Saint-Louis	2012	0	0	0	0	0	0,0	**74,0**	**107,1**	**197,7**	**8,0**	0	0
Saint-Louis	2013	0	0	0	0	0	0	**59,9**	**151,4**	**151,7**	**3,5**	**0,5**	**7,8**

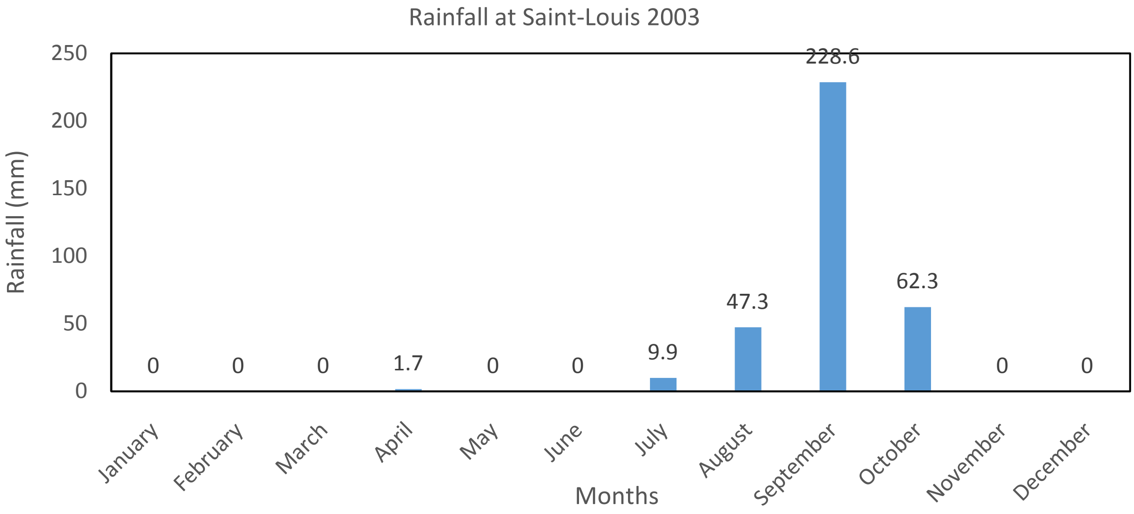

Figure 2. Rainfall at Saint-Louis 2003

3. Methodology

Samples were taken from the Langue de Barbarie and the breach. Three types *of soil* were sampled: banco shell (M6), sand dune (M7) and fine sand (M8). In the laboratory, samplings were studied to obtain a representative sample before being subjected to full identification and mechanical characterization tests. The laboratory tests were carried out with the support of the Experimental Center for Research and Studies for Equipment (CEREEQ) in Senegal.

4. Results and Discussions

The geotechnical characterization focused on the granulometric analysis, the determination of the state of the soils consistency, the determination of the blue value of the soils and the oedometric compressibility test. Table 2 summarizes the results of the geotechnical characterization of soils taken from the Langue de Barbarie.

Granulometric analysis can detect, reduce the size and the respective weight percentages of the different families of grains constituting the sample. The results of the granulometric tests carried out on the three samples (M6, M7 and M8) taken from the Langue de Barbarie are presented in Figure 3. The results show that the M6 sample is composed of pebbles, gravel and sand, whereas the M7 and M8 samples consist mainly of very narrow and poorly graded sand (Figure 3). These observations indicate the formation of sandy banks following the passage of the breach since it is not stable and it moves according to the speed of the winds and swells. The consistency states of the sampled soils were determined by the Atterbert limit test according to the NFP 94 052 1 standard. The test was carried out only on the M6 sample which has a higher percentage of fines (Table 2). The results of the test reveal a plasticity index of 14% of the soil (Figure 4). The casagrande diagram (1948) classifies the M6 sample in the group of weakly plastic inorganic clays (silty and sandy clays). The blue value of the samples were determined by the blue test according to the NF P 94-068 standard. The results of the methylene blue values confirm the slimy character of the M6 sample (Table 2). However, for the M7 and M8 samples, the methylene blue values are relatively low and correspond to those of slimy sand (Table 2). The GTR classification system places the soils of the Saint Louis among the sandy and gravelly soils with B6 fines for the M6 and B4 samples for the M7 and M8 samples.

The oedometer compressibility test was performed on the M7 sample intact. The results of the measurements of the height variation of the soil sample as a function of the loads applied are shown in Figure 5. From this figure, we deduced the compressibility parameters that give indications on the swelling potential of the M7 sample, its history and its behavior under load. The preconsolidation pressure was determined by the extension of the two linear slopes of the consolidation curve. It is about 1.25 bar (Table 2). The coefficient of compressibility (Cc = 0.025) obtained is typical of a sand that is not very reliable. To analyse of the coefficient of swelling (Cg), we studied the swelling character of the studied soil. It revealed that the M7 sample has a swelling coefficient of less than 0.3 (Table 2) which, according to Philipponnat's (1978) classification, corresponds to a low swelling.

Table 2. Physical and mechanical characterization of Langue de Barbarie soils

Test	Particle size distribution					Atterberg Limit test		Methelene blue test	Compressibily			
Sampl.	0,08 mm	2 mm	5 mm	C_u	C_c	w_L (%)	I_P (%)	VBS	e_0	C_c	C_s	σ'_p
M6	**14**	**71**	**75**	-	-	**14**	**14**	**2,48**				
M7	**2,2**	**100**	**100**	**1,38**	**0,87**	-	-	**0,66**	**0,97**	**0,025**	**0,004**	**1,25-**
M8	**4,8**	**100**	**100**	**1,39**	**0,81**	-	-	**1,16**	-	-	-	-

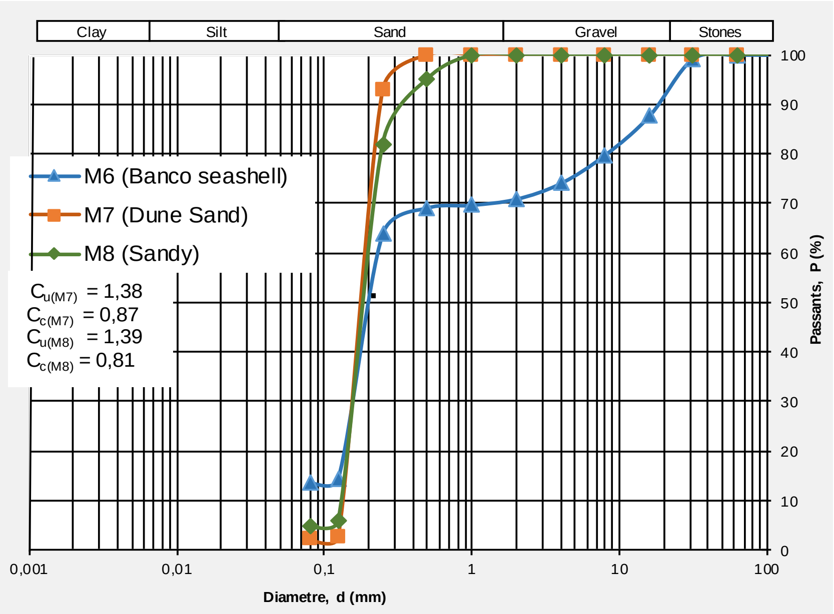

Figure 3. Granulometric curves of soils of the Langue de Barbarie

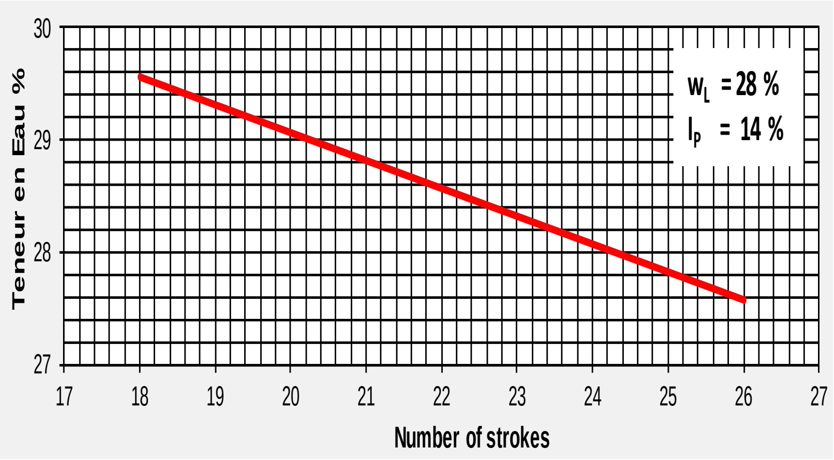

Figure 4. Liquidity limit of the M6 of sample

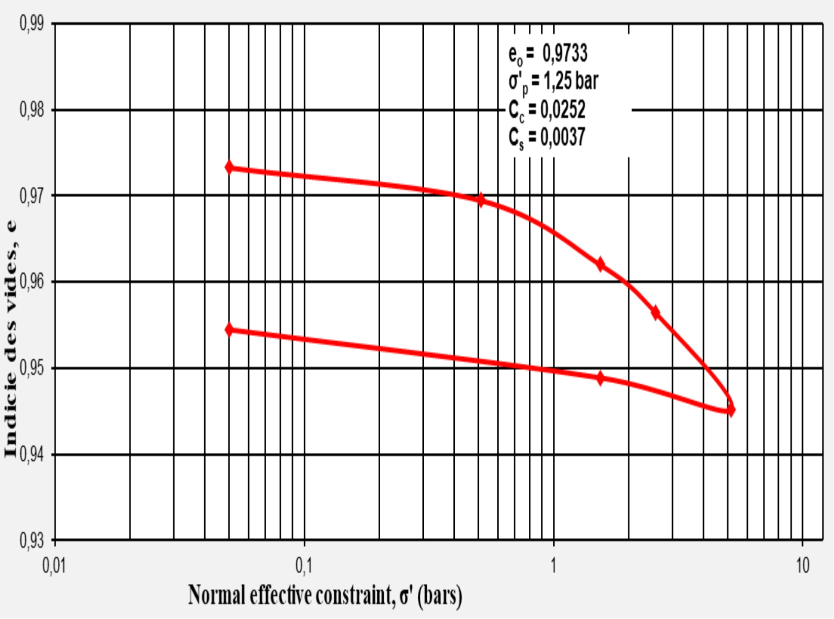

Figure 5. Compressibility curve of M7 sample

In view of these results, structural methods and non-structural methods are proposed as stabilization techniques.

4.1. Structural Methods

4.1.1. Laying Blocks of Laterites

The work to be done consists of a local riprap in blocks of laterite (Figure 6). The implementation of the structure must respect the slope angle of the laterite blocks with a sufficiently slight slope to ensure the stability of the riprap. A Lateral riprap is a credible alternative to the current operation of the mouth zone and the choice of the location of the structure (50 m before the Gandiol lighthouse and 650 m after on the same line to the south)). This structure can be a durable solution because the structure will be sufficiently resistant to the force of the waves. This option does not require fattening or geotube accompaniment. The laterite blocks (available in Senegal) are placed on the limits of the beach at high tide, over a minimum height of 1 m and a width of 20 m according to the specifications provided by the study. And to minimize the effects of scouring, we can expect the installation of a geotextile.

The costs associated with the application of this technique can be economically sustainable because it does not require repetitive maintenance work and the materials used (laterite blocks) are not vulnerable to the involved forces. In the context of the southern migration of the breach, the materials that will be currently used opposite the village of Pilote-Barre are transportable and reusable in the future on other sites further in the south (Tassinère for example) to the direction of the migration of the breach.

However, the force that will be exerted by the mass of the blocks may create a scour of the structure by undermining phenomenon at the bottom of the embankment slope. This requires the establishment of an anti-scouring mat. Moreover, it is possible to significantly reduce the cost of development by making adjustments to the width of the structure and its height without altering the capacity of the development to minimize erosion in gandiol. Thus, since the lining starts from the current limit of the beach at high tide, instead of making a rock surface over 20 m wide, 10 m wide would be sufficient to achieve the expected results of the work because according to the results of the hydrosedimentary analyzes [10], the wave breaking zone is located on the low range. The geotextile planned to fight against the very likely scour of the structure could be replaced by the digging of a channel which will have to receive the foot of the work.

Figure 6. Laying blocks of laterites

4.1.2. Realization of Breakwaters

The breakwaters will be parallel to the shore and located on the beach front (Figure 7). Their function will be to oppose directly the swell as well as the flow of currents perpendicular to the shore line. These breakwaters will also oppose solid movements in the profile of the beach. Since the breach widens under the action of wave energy, marine currents and coastal drift, these breakwaters will act in two ways:

- The reduction of the blades energy, which reach the level of the shore, consecutive to the reflection and the surge of the swell; The spread of wave energy behind them due to the phenomenon of diffraction around their extremities and refraction on the bottoms they modify.

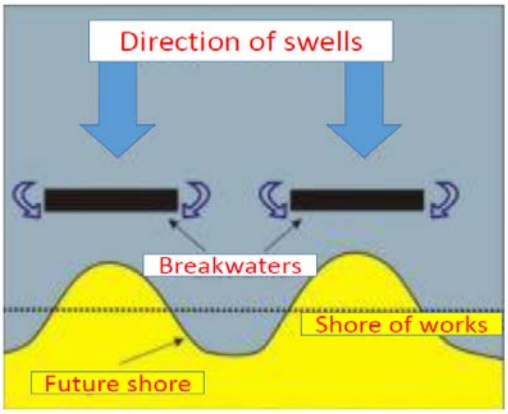

Figure 7. Laying blocks of laterites

The breakwaters can be emerged or completely immersed. The emerged structures generate between them and the coast, a zone of relative calm favorable to sedimentation. The submerged structures limit the volumes of water that will cross them and force to welter the swells that exceed a limit arch.

4.1.3. Achievement of ears

The ears are perpendicular to the shore and they reduce or even interrupt the hydrosedimentary transit (Figure 8). The spikes act only on fluid and longitudinal solid movements with respect to the coastline. They cannot therefore oppose the erosive actions of return currents or sagittal currents which operate in the vertical normal section to the coastline. By stopping coastal transport, the spikes produce accretion on the upstream side of the resulting solid transport and erosion on the downstream side of the resulting solid transport. The establishment of ears therefore modifies the line of shoreline which tends to come, between two ears, perpendicular to the ridges of the dominant swells. This modification tends to accentuate even more the limitation of littoral transit by swell, which is almost nil when the shoreline is parallel to the ridges of dominant swells. The batteries of ears thus tend to stabilize the profile of the beach by making it evolve towards its natural profile.

To stabilize a portion of coastline, the ears must be arranged in series. Their installation must begin at the downstream side of the solid transport and continue upstream of the solid transport as they are bypassed. Along the defense, the ears must all be in the same length.

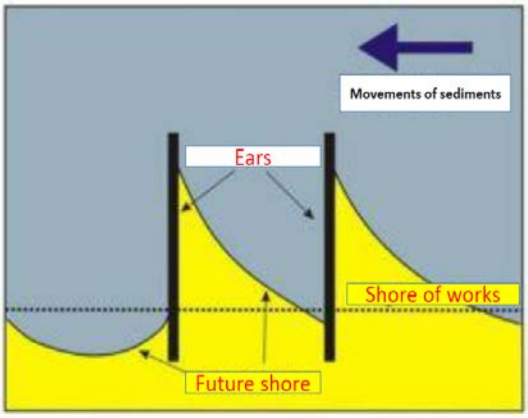

Figure 8. Ears

4.2. Non-structural Methods

The so-called "soft" solutions make it possible not only to "defend" against the sea but also to "cope with" the phenomena of natural processes that intervene in the evolution of the coastline. Therefore, the approach is no longer to consider a "fight" against erosion, but a continuous "management" of the coastline integrating its natural dynamics and its mobility.

4.2.1. Artificial Reloading in Sediment

Since the breach creates a sand loss from the coastline transport (Figure 9), the reloading in sand will aim to compensate this deficient sedimentary budget without disturbing the natural the processes in action of the coast.

The supply can be done if possible from a sand exogenous to the hydrosedimentary cell (inside zone which the sediment circulates with little or no exchanges with the outside) or then located in the zones of accretion of the cell or at too great depths (beyond the depth of closure) to regain the beach under the effect of natural hydrodynamic processes. The artificial fattening of the beach will increase its ability to protect the coast, absorbing wave energy.

Figure 9. Artificial reloading in sediment

This method has a very natural appearance and does not have negative effects on the beach and the surrounding land. However, it requires recurrent maintenance and may, in some cases, represent significant investments and require environmental studies.

4.2.2. The Draining

The principle of the device is to install drains in the area of the streams in order to facilitate the infiltration of water deposited by the wave flow and lower the roof of the aquifer (Figure 10). The objective is to obtain a dissipation of the energy of the withdrawal water (reflux of the water) and to favor the deposit of sand (which does not restart with the reflux).

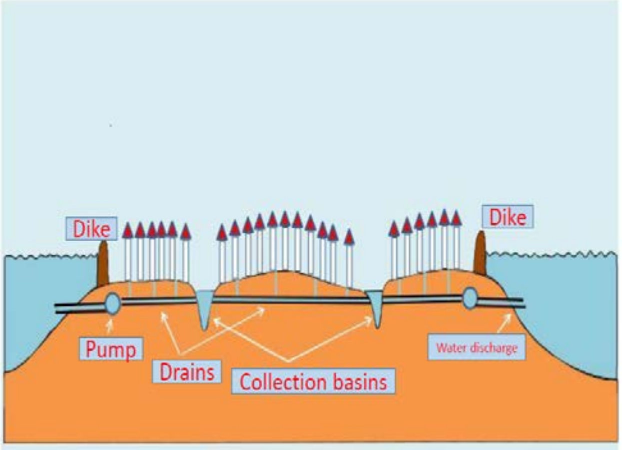

Figure 10. Draining

Concretely, the drains are installed in a depth parallel to the shore and are connected to a pumping station that collects and discharges water to the sea or to the recycling stations. The advantage of drainage is to reduce landscape impact, except during construction. Sand, in the throw area of the shore, being drier, is popular for recreational activities.

5. Conclusion

The Langue de Barbarie is a fragile environment and almost all the economy is organized according to the particular configuration of this site. The opening of the breach at October 2003 has led to many changes and new constraints in terms of occupation and use of space, although the canal has been dug to mitigate the risk of flooding. The decision taken urgently, without study taking into account all the economic and ecological constraints caused many environmental problems changes in the biophysical characteristics of the area (floods, loss of biodiversity). It was realized that the problem to be solved initially created other problems because the intervention had been miscalculated. These setbacks can be explained by an insufficient knowledge of particularly complex natural phenomena on the coasts. The results of soil sample analyzes made it possible to propose structural and non-structural stabilization methods. Meanwhile, non-structural methods are less expensive with a need for periodic monitoring by drone.

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