NATURAL VERSUS ANTHROPOGENIC FACTORS IN CANCUN BARRIER EROSION

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During the first half of 2006 important sand nourishment was done along the barrier shore face of Cancun Nizuc (Quintana Roo, Mexico). It was quickly decided and constructed after that the hurricane *Wilma* swept the barrier and under the recent general impression of the devastating *Katrina* effects on New Orleans region. That decision interrupted a long time of discussions about the better Project to recover the great erosion of the barrier beach. This paper discuss the role of the different natural agents on the coastal erosion in this Cancun barrier under strictly natural conditions, trying to discern the relative importance of the common maritime weather versus the hurricanes; and the role of the different anthropogenic agents of development in both the generation of new erosive coastal processes (strictly anthropogenics) and the strengthening of the previous and natural processes (partially anthropogenics). The later being more significant, the paper looks at the different importance of their synergies with the, respectively, common weather versus hurricanes effects on the barrier erosion.

INTRODUCTION

The Cancun-Nizuc (Benito Juarez, Quintana Roo, Mexico) coastal barrier (Figure 1) has suffered dramatic reduction since 1970. An important and hasty tourist development has been taking place, by the alongshore occupation with condominiums, hotels and other facilities of a great part of the barrier; this occupation affected in many stretches most of its wideness including dunes and even, some times, part of the beach. This way of development had as consequence the onset of a permanent unsteadiness of the beach, and the subsequent setting of the erosion conditions on, at least, some of its stretches, though they were not well noticed for some not specially storming time (Diez and Esteban, 2006). The erosive situation became suddenly and dramatically evident in 1988 after the *Gilbert* event. Among the effects of hurricane *Gilbert* the erosions suffered by the beaches of the Nizuc-Cancun barrier acquired special meaning, although they had to be presumable taking into account the placement of the buildings of the excessive tourist development, doubtless too much close to the shoreline, even built on the active profile of the beach.

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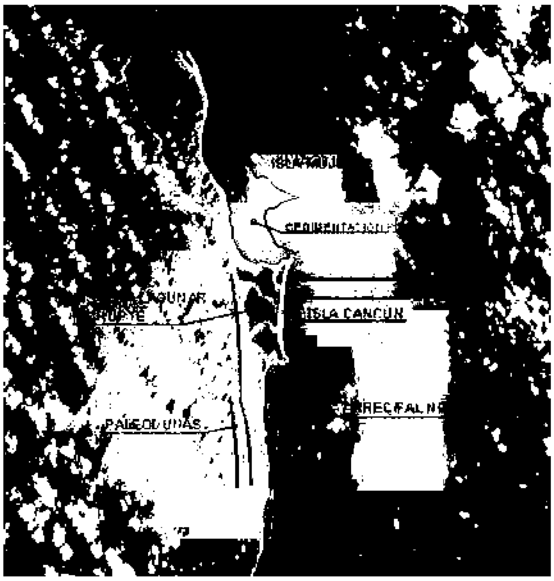

Figure 1. Localization of the Cancun-Nizuc beach barrier (CFE, 2000-2001).

The effect on tour operators became important, reducing local incomes and becoming to have a main effect on socio-economic activity of the whole estate. As a result of the *Gilbert* impact some studies were immediately undertaken by UNAM (1989-1991) looking for adequate knowledge of the problem and processes to aboard a well founded regeneration project for the whole barrier; it delayed and some local owners, mainly hotels, projected a few small constructions, for local protection in different few short stretches of the barrier beach, with little satisfactory results.

By the turn of the past century most of the barrier length scarcely had permanent beach and the wave attacks on the hotel structures became very frequent. Socioeconomic damages by the affection of tourism were already important at that time and environmental impacts were presumed to be happening, not only on the coastal barrier and its beaches but in the ecosystem of Nichupte lagoon as well if the barrier became broken. Therefore local authorities promoted new studies to understand as accurately as possible the behaviour of the whole barrier system and surroundings. Several additional studies were so developed until 2004 (CFE, 2000-2001; CFE, 2003), initially aiming to come forward with a solution for the recovery of the beaches and the permanent protection of the barrier.

The erosion (Figure 2) was even more serious after passing new different hurricanes throughout the zone, especially *Ivan* (2004) and *Wilma* (2005). *Wilma* trajectory run parallel onto the barrier from south to north and had a notorious impact on the whole barrier installations, probably being determinant of the beach recovery decision, taken at the beginning of 2006. The regeneration was developed along the fist half of the same year, apparently as a simple nourishment of the whole barrier beach, although no professional information could be obtained about it.

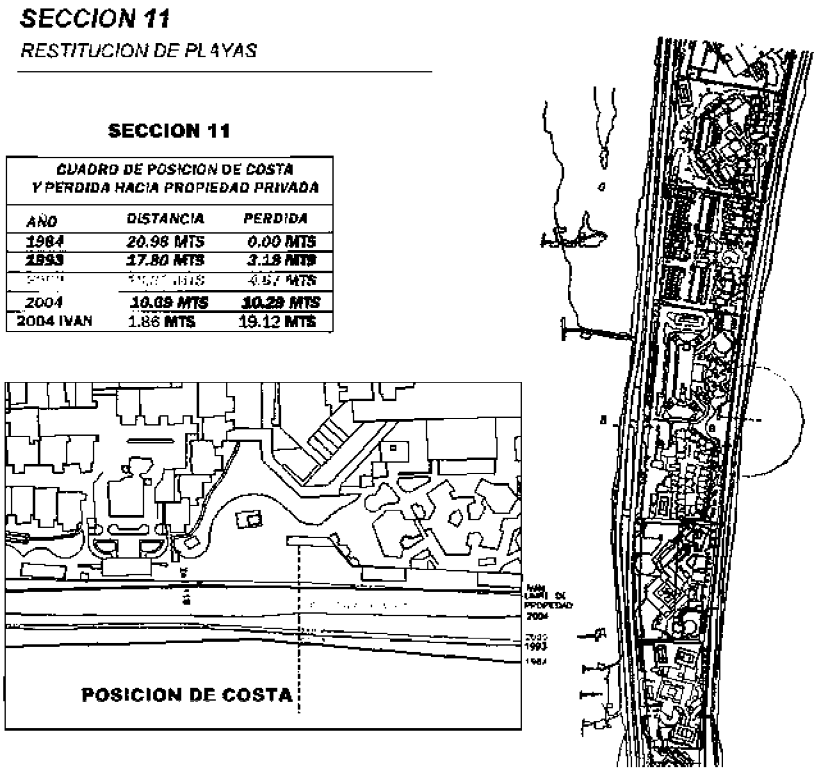

Figure 2. Typical evolution of shoreline in Cancun. The regression of the shoreline is practically continuous in all sections and had reached dramatic reduction of the beach in many of them.

ZONE DATA

The continental part linked to the Cancun-Nizuc area has the same nature than the rest of the Yucatan Karstic formation since the Pliocene (Diez, Esteban and Paz, 2009). The sea platform is so from Karstic origin and constituted of calcareous material. The present landscape began to take shape in the late Pleistocene; Nizuc and Cancun have initially constituted islands and the littoral barrier between them was developed under Aeolian and northward littoral actions, probably induced by an underlying reef system that could be extended as far as the Mujeres Island. The bay between it and the continental shoreline became a coastal lagoon which evolved to the current Nitchupte lagoon.

Former barrier was extended as a spit as result of the longshore transport, probably till Mujeres Island, changing later northwestward its direction as a consequence of a colder climate (Diez, Esteban and Paz, 2009). Lagoon, barrier and spit have been submitted to sea level and other climatic conditions along the Holocene permitting the formation of two *tombolos* respectively sheltered by Cancun and Nizuc points. The Cancun and Nizuc island system became, thus, to prevent the sea water flowing to the lagoon and allowed a freshwater/estuarine ecosystem. This former barrier, of about 17 km. length and 100 – 400 m. width initially, has evolved loosing the sandy spit and reducing its length to 12 km. Part of the ancient barrier and spit still remain as sand banks and islands (Diez, Esteban and Paz, 2009)

Current water circulation is restricted in the lagoon system only flowing seaward through a few narrow tidal channels between both *tombolos*. The barrier had accumulated Aeolian materials reaching significant heights in some dunes, but most of the sandy material was removed afterwards. The beach had before fine sands but now, due to the erosions, the sediments show a triple origin: the notably gross sands and coarser materials are from the reefs, the carbonated finest sands deposited by saturation, and the organogenic sands and shell rests; the three can be identified in the size grain distribution curves of these studies.

It is necessary to separate in this area the so called ordinary or common wind waves, corresponding to the regular maritime climate, with its extremal wind regime, corresponding to the storm waves, and the regime due to hurricanes. Although the effect of extreme common storm waves is important respect to the rest of the common waves, is quite small in relation to the effect of hurricanes when directly affecting the study point. The analysis of the average wind wave distribution seems to clearly show a certain climatic bi-seasonality (winter-summer), much more illustrative and meaningful than the division in the four classic seasons (astronomical), which have not only climatic meaning. The winter spans from September to mid February, with storms coming from the NE, and the summer goes from February to mid September, with storms coming from SE. February and September are transitory periods with the respective roles of spring and autumn (Diez and Esteban, 2006).

The effect of hurricanes does not depend in fact only on their magnitudes, but also on their trajectories and diameters. And according with the continental shelf shape the refraction is always important, being maximum for the north-eastern offshore waves (CFE, 2000-2001) (Figure 3). The referred studies show that the potential transport of sediments due to hurricanes such as *Gilbert*, that only lasted a few days, are not much greater than those due to common wind waves, that run along the whole year.

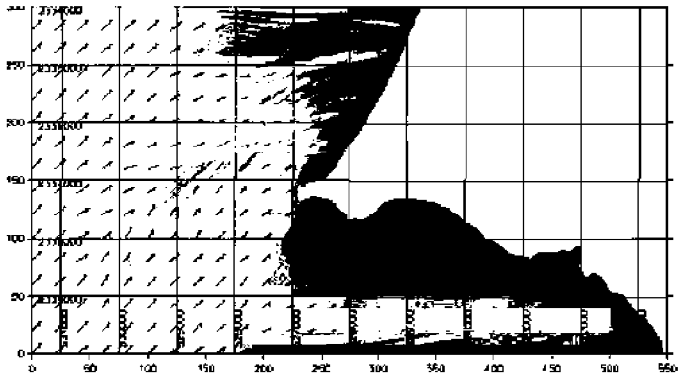

Figure 3. Application of the Model refraction of northeast waves (CFE) showing a strong, but likely insufficient, change of the waves direction. The northward drift is dominant.

A northwards net longshore littoral transport throughout the barrier seems to be obvious, and a natural feeding of sediments to the barrier system takes so place from the south in front of Nizuc point, but this feeding is lesser than the northward losses in front of Cancun point, whose rocky support is not able to hold the littoral transport. It also shows the existence of a transversal swing of the beach cross profile moved by the transversal littoral transport and whose net balance is estimated seawards, mainly due to the difficulty for the recovery of the sand material (difficulty mainly caused to the dyke effect of the natural reefs, outcropped by erosion and still rather unknown, not researched nor sufficiently mapped in the studies, and whose destabilizing role on the beach profile cannot be ignored. These outcrops do not appear reflected in charts and bathymetries before Gilbert event and only begin to be increasingly noticed in bathymetries and cross profiles made since UNAM studies (CFE, 2003).

Most of cross profiles along the beach are monoparabolic; only in some zones in the barrier, those placed in its extremes, a little "step" can be distinguished like a reminiscence of the bar. Bathymetric data managed make us think a loss of that "step" since 1985 (CFE, 2000-2001; Diez and Esteban, 2006). The sedimentologic analysis let us to recognize a close relationship between the materials from extraction banks and the materials from the beaches and dunes, and between all of them and the materials of the reefs (Diez and Esteban, 2006).

DEVELOPMENT OF THE STUDIES

The Institute of Engineering of the UNAM conducted a research from 1989 to 1991 at the request of the *Fomento Nacional de Turismo* (FONATUR). They determined topographic and bathymetric characteristics, coastal and maritime weather and storm surges, and the refraction of the wind waves; they also studied the nature and behaviour of the sediments. A solution to solve the erosion problem was proposed. This study separated already the so called ordinary/common wind waves from those produced by hurricane conditions and referred to as cyclonal waves (the hurricanes Gilbert, Carla, Carmen, Beulah and Allen are likewise mentioned) (CFE, 2000-2001). They might have assumed that the wave distribution of the latter could be considered as the extreme wave distribution of the former. This hypothesis would not be entirely appropriate because they actually are two different types of climatic phenomena.

As a consequence of the recovery phase of the natural cycle of any beach (Copeiro, 1978) the initially (1989) apparent recovery of beaches soon after Gilbert was expected to continue. Nevertheless, later observations recognized that this natural recovery stopped soon, if it actually happened at all, and was only confirmed in the ends of the barrier. As a matter of fact, this accretion of the barrier ends could be due to the combination of both the barrier and the sheltering effects of the rocky extremes of the barrier during the time of intense longitudinal transport caused by Gilbert. The slowness of this natural recovery of the beach up to 1990/91 determined an early change in the initial diagnostics, notably about the need for some artificial way of protection or regeneration was taken into consideration (CFE, 2000-2001).

Wave refraction was calculated using diagrams obtained by means of numerical models and it results maximum for north-eastern waves. However, no special meaning was given to this finding. In our opinion, this strong refraction of the first quadrant waves can be estemated merely observing the bathymetry in deep waters in front of the barrier (Figure 4); and this significant refraction explains the predominance of the northward longshore littoral transport.

The littoral transport (CFE, 2000-2001) is obtained in those studies by empirical formulas that, although generally accepted, provided hardly consistent results, perhaps due to the problems of a suitable modelling of the wave refraction. Ordinary waves generate a littoral transport that widely depends on the formulations made and on the considered stretch of the barrier (net longshore transport: between 7,000 m^3/year northward and 610,000 m^3/year southward; seaward transversal transport: between 1000,000 and 1700,000 m^3/year). *Gilbert,* however would have generated 130,000 m^3 net offshore transport and between 6,500 and 256,000 m^3 northward longshore transport, also depending on the applied formulas and estimated waves (CFE, 2000-2001). On the other hand, the calculated littoral transport is just potential (i.e. capability of transport) and the studies do not show the availability of sedimentary materials which could allow this calculated transport to actually take place.

New studies (developed in three stages) to establish a diagnosis and to provide and update the data were made by CFE (2.000-2.001). They reviewed and extended the studies made by UNAM in order to draft a project for “integral rehabilitation of the beaches between Punta Cancun and Punta Nizuc”. And CFE proposed a later and final report in December 2003. Oceanographic, geotechnical, topographic and hydrographical research was conducted in the first stage of these studies in order to complete the information about sediments.

UNAM's conclusions were reviewed and a first diagnosis critically revised its previous assumptions. In a certain way, studies at this stage followed the working lines of the research made by UNAM, but correcting and completing them thoroughly.

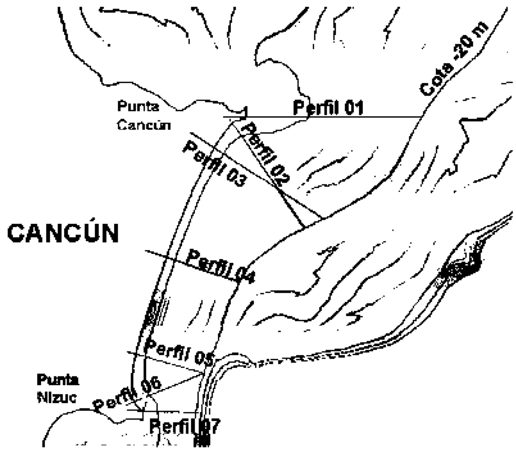

Figure 4. Bathymetry in front of the barrier (CFE). Notice the differences in the slope from the north to the south, that favour a stronger northwesternwards refraction under practically any wave conditions.

The second stage of these studies were finding alternatives for the beach recovery works and nourishment, studying the beach profiles and evaluating the sandbanks nearby (Diez, Esteban and Paz, 2009). The data obtained in the previous stage was reviewed and taken into account to make an analysis of the movement of the coastline. Erosion limits were established, and a good analysis of the variability of the beach cross profiles is also incorporated.

The third stage contains new sediment data of the banks of extraction and of beach and dune sands, new wind wave and surge studies and a satellite photograph showing the sediment passage in front of Cancun point towards the Bay of Mujeres Island. At this stage a construction project was proposed, consisting of beach nourishment and some stabilizing works (Diez, Esteban and Paz, 2009). CFE proposed in its later report (December 2003), however, a new construction project totally free of rigid works, consisting of just sand nourishment.

This final report made evident the existence of a net longshore littoral transport northwards throughout the barrier, and of both a natural feeding of sediments to the barrier system from the south in front of Nizuc point and a drainage of the sands in front of Cancun. That feeding had to be smaller than the northward losses through Cancun section, whose rocky support cannot hold the material from the littoral transport. It also showed the existence of a transversal swing of the beach cross profile caused by the transversal littoral transport and whose net balance was estimated seawards. The difficulty for the recovery of the sediments (possibly caused by the dike effect of natural reefs, outcropped by erosion of the sands around) had a destabilising role on the beach profile which cannot be ignored. This presumptive outcropping was not reflected in the charts and bathymetries before *Gilbert* and only began to be increasingly noticed in bathymetries and cross profiles after the UNAM studies, but they have never been evaluated before (Figure 5).

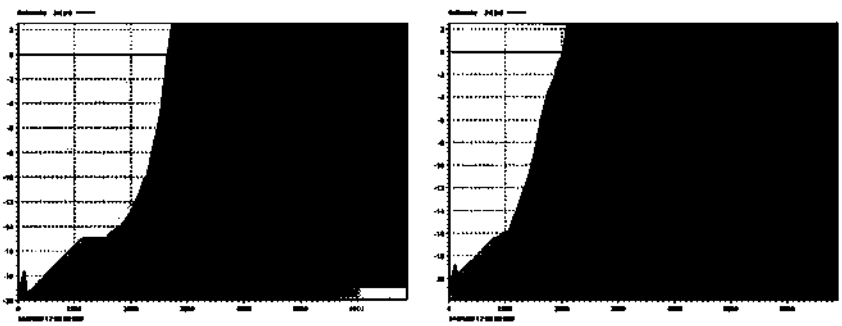

Figure 5. Typical cross profiles: monoparabolic till farer than common Cornaglia point, showing however residual and witness reefs.

HURRICANES

Hurricanes are frequent phenomena in the Cancun-Nizuc barrier. This barrier has suffered the consequences of different hurricanes (Table 1). Due to the influence in the erosion of the Cancun-Nizuc barrier, events are deserved to be emphasized are *Gilbert*, *Ivan* and *Wilma*.

Table 1. Critic features and critic time of several hurricanes in the zone in 1961-1988 (CFE).

Hurricane	Date	Direction	P_o (mb)	H_s (m)	T_s (s)
Gilbert	September, 1988	71,5º NE	675,17	12,00	13,83
Carmen	September, 1974	69º SE	755,44	2,19	9,89
Carla	September, 1961	77º NE	751,69	5,23	9,1
Beulah	September, 1967	26º SE	751,69	5,18	9,06
Allen	August, 1980	11º SE	747,94	6,64	10,27

Gilbert happened in 1988 and it has been the most devastating hurricane on the beaches of the Cancun-Nizuc littoral barrier due to its force and extension, but also due to it path (Figure 6). This event made evident the erosion in those beaches.

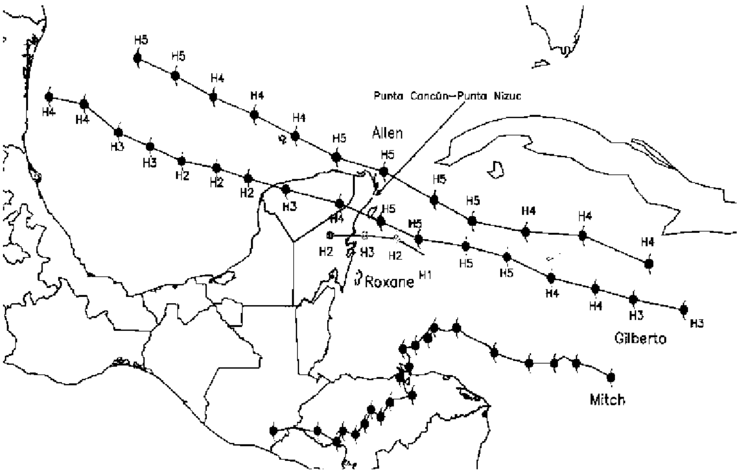

Figure 6. Trajectories and forces of different hurricanes: Gilbert, Allen, Match & Roxane (according CFE)

Ivan (2004) affected Cancun beaches from faraway, generating wind waves with relative southeastern incidence and causing northward littoral transport on the barrier, just the worst case for it. Although the damages could be worse, in the worst moment, the position of *Ivan* generated a very powerful wind wave storm with northeastern incidence permitting the recovery of the beach barrier. Also, its path (Figure 7) turned north before reaching the barrier, generating a smaller storm tide (surge level) on Cancun than *Gilbert*.

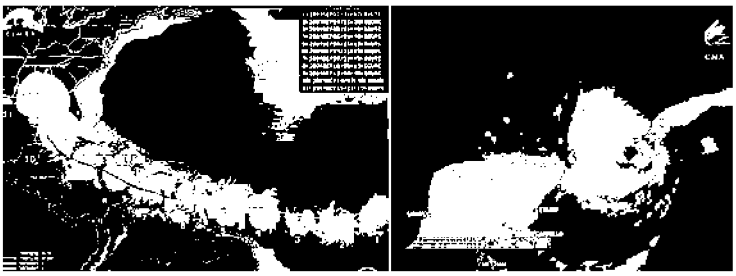

Figure 7. Trajectory of *Ivan* in last position over Cancun area

Wilma (2005), whose trajectory was parallel to the barrier, from south to north (Figure 8), had a greater effect than *Gilbert*, especially because of the permanence and longshore evolution of the waves, and in spite of a lesser degree of intensity in front of this coast. During faraway trajectory, *Wilma* could be more aggressive against Cancun beaches because wind waves incidence was even more southeastern than *Ivan*'s but the worst situation was produced during the time when *Wilma* slowly evolved in front of and over coastal zone (Figure 9). All this time, incidence of the waves remained from the southeastern.

Besides, the intensity and magnitude of erosion on the beaches and dunes had already caused (even previously to *Gilbert)* important damage on the whole barrier, affecting tourism, with risk for its stability and its integrity at some points.

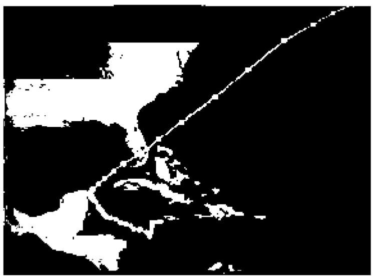

Figure 8. Trajectory of *Wilma* hurricane over Cancun area

Figure 9. Three pictures of the evolution of *Wilma* in a stretch path in front of Yucatan peninsula, in Cancun area

DISCUSSION

The analysis of the average wind wave distribution clearly shows a certain climatic biseasonality (winter-summer), more illustrative and meaningful than the division in the four classic seasons (astronomical). Winter spans from September to mid February, with storms coming from the NE. Summer goes from February to mid September, with storms coming from SE. February and September are transitory periods playing the respective roles of spring and autumn. This biseasonal grouping allows a better analysis of the real coastal processes. The same climatic features take place in many zones of the planet (Diez, Esteban and Paz, 2009) and should be taken into account in similar studies.

The ordinary waves are not statistically related to the hurricane waves. They have an annual average distribution and an extreme value distribution; the former (*wave regime*) is appropriate to analyze sediment transports and coastal processes and the latter is appropriate to estimate stress and other mechanical design variables. Statistical estimates of the hurricane wind wave regime in a determined point of the coast may not make much sense due to the lack of data, as the number of hurricanes in zones of similar situation, geographically assimilable to the observation point, is very scarce. The hurricane analysis conducted in these studies may be correct, and valid for a generic point of observation in the Gulf of Mexico. However, it must be avoided for specific areas, such as Cancun barrier; and cannot be used instead of the extreme value distribution of the ordinary waves because hurricanes (tropical conditions) have different climatic circumstances than the extratropical cyclones or trade winds.

The previous assessment is relevant in the analysis and design of littoral rigid works and also in the problem analysed here. The significant variables for the management of this kind of coastal processes come from either ordinary waves or hurricane analysis: the former in the “prevailing” coastal processes and the latter in the processes under hurricane conditions.

The potential littoral transports were calculated using average wave distribution that is different from the classic regimes based on exceeding along the average year. The obtained littoral transport values obtained are smaller when formulations like Coastal Engineering Research Center ones are used. There is a threshold wave height necessary to move each grain of sediment, and a non-lineal relation between the transport and the wave heights. Because of this, the transport generated by waves below the average wave is smaller than that due to the waves above the average one. This can imply the existence, under ordinary waves, of capacities of transport greater than those that had been calculated before.

The effects of extreme common storm waves, although significant in relation to the rest of the common waves, are quite small in comparison with the effect of hurricanes. The CFE study omits their extreme wave distribution, making hurricanes the determinant cause of the extreme impacts; not only for surging level estimation but also for the forecasting of catastrophic wave processes on beaches. As Cancun barrier has already undergone the powerful *Gilbert* effects, however, its observed values must be more appropriate than the lesser regime values determined with any pseudo-statistical method. The statistical analysis of the hurricane surge level and waves is perhaps appropriate, and undoubtedly convenient for the whole Caribbean area and for its different zones. Nevertheless, it does not have a relevant meaning here because it is based on a small number of hurricanes (Table 1) and also because all of them have different statistical parameters in the study point. Therefore, the recurrence determined for *Gilbert* can be considered worthless.

Waves suffer an intense refraction, greater than that anticipated by theoretical models, (Figure 3), which are commonly accepted and do not correspond sufficiently to the bathymetry of the continental slope and shelf in front of the Cancun barrier. It affects negatively both the evaluation of the sediment transport and the risk of the beach erosion.

Some geomorphologic data of these studies are also remarkable and it is possible to conclude observing the bathymetries that reef outcropping has been increasing after *Gilbert*, as a result of the erosion and the descent of the profiles. Besides, the erosion of the reefs themselves obviously increases when they outcrop, providing thus the gross fractions of the sediments and samples. These studies do not supply so far, though, any accurate information about the presence or outcropping of reefs and the possibility of obtaining it now, after the nourishment of the beach, has become very low until posterior erosion, but it is still very convenient. The knowledge of the distribution and nature of reefs, announced by the comparison of the bathymetries of 1985 and 1989 could certainly be improved. That comparison permits, however, to conclude that the reefs increasingly outcropped in those years and that the erosion of the beach profile along the entire barrier was also more significant then. The reefs affect the natural changes and evolution of the cross profiles and may have been playing a destabilising role on them. The available studies have not taken into account the effect of such reefs on the transversal transport processes.

Marine climate in these latitudes is characterized by a bimodal wave distribution in deep waters, with dominant waves from NE from mid September to early February (period that can be called winter), and dominant waves from SE from mid February to early September (summer). The wave propagation until breaking implies a change of direction according to the bathymetry of the zone next to the coast, and the change is greater with NE waves. Therefore there is a net northward alongshore transport with loss of sediments in front of Cancun. Cancun point cannot retain all of them, and the transversal transport caused by hurricanes can aggravate the problem. Sediment supply to the system, run by SE waves, takes place mainly in summer coming from the south in front of Nizuc.

The alongshore transport under common waves is generally restricted to a limited band which permits Cancun point to retain a great part of sediments. Before the development of the barrier, the losses in front of Cancun due to the transversal transport along the barrier were limited, because of the fast recovery of "prevailing" profiles after the storms. Before the appearance of reef outcroppings, hurricanes implied a large swing of the profile, with a strong incidence in the longshore transport and losses of sand, but with a fast recovery of the profile. The normal loss of sediments in front of Cancun could be easily compensated each year with the increase of sediments in front of Nizuc point; and the extraordinary losses under hurricane conditions could be also compensated in a few years.

Development has increased along the shoreline, even on berm and dunes, reducing the "resilience" of the beach profile for the different sea states. As a consequence, a continuous erosion of the coast was unavoidably induced and made worse when hurricanes appeared (Figure 2). The possibility of cross profile recovery diminished, its bar reducing and its slope increasing, and the reef outcrops probably appeared. Under these conditions the sea level reaches more easily and frequently the (rigid) structures that confine the hotel facilities, which accentuates wave reflections undermining the profile. The removal of the sediments facilitated their transport towards the barrier in front of Cancun. Common waves, in addition to hurricanes, were, to sum up, increasing their efficiency on beach erosion.

CONCLUSIONS

When the *Gilbert* hit the coastline, the beach was already eroded, its bar very reduced, its profile sloping and getting deeper and, perhaps, with multiple outcropped reefs for that time. The transversal off-shore transport due to *Gilbert* storm and surge moved away a significant volume of sediments offshore beyond the reefs. *Gilbert* could have stricken the zone prior to the profile transformation; then the recovery of the beach would have been probably greater and faster: It took place however after that the slope had deepened and, possibly, that a remarkable amount of reefs had already outcropped, so that the common waves were not able to return the sediments towards the land again.

The problem of beach erosion apparently manifested for the first time in Cancun after *Gilbert*, but these studies permit to state that the hurricane only magnified a problem that had been livilng for a long time. Its origin would be attributed to the occupation process of the barrier. The idea that climatic sea level rise could have unleashed the process must not be taken yet sufficiently consistent hypothesis, otherwise it would have been proposed before. The study does not provide any sign of submersion in this coast.

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