Chapter 13
From Sediment Movement to Morphodynamic Changes, Useful Information from the Modeling World to the Beach Management Practice

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Abstract Beaches respond in several time and space scales to physical phenomena like wind, waves, tides, storm-surges, littoral currents, river discharges and sea level rise. As a dynamical system they can also be changed due to the influence of biological, geological and chemical processes as well as human-related activities such as urban expansion and port development; construction of coastal protection infrastructure; resources extraction or production and, tourism related actions, among others. In order to properly manage the beaches, any proposed plan or program should preserve the natural structure and function of the beach. In this sense, coastal managers need to choose among several scenarios and managerial options based on the best scientific information available, and one of the most adequate method to do that -considering the cost/benefit-, is looking at the results of coastal simulation models. This paper is focused on coastal processes and review some empirical and numerical models emanated from the coastal engineering arena that can be useful in the practice of coastal management; identify the stages of management in which should be used; and proposes strategies for the proper implementation, monitoring and review of the modeling results, in the context of local beach management.

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13.1 Introduction

Coastal regions are complex and dynamic features of the landscape (e.g. deltas, estuaries, salt marshes, intertidal flats, dunes, beaches, cliffs, coral reefs, etc.) driven by physical, geological, chemical and biological forces and processes. To study the forms, process and evolution of the coastal environments, the concepts of "coastal system" and "coastal morphodynamics" have been employed around the world (Wright and Thom 1977; Short 1999; Woodroffe 2002). This paper focused on the morphodynamics of wave-dominated beaches (dynamic interactions among near-shore topography, fluid dynamics and sediment transport), considering engineering time scales -months to decades- in its adjustment time (Masselink and Hughes 2003), within the framework of coastal management and considering the use of simple modelling tools.

According to Short (1999), the simplest definition of a beach is a wave-deposited accumulation of sediment lying between the maximum depth at which waves can transport beach material shoreward, and the landward limit of sub-aerial wave action and sediment transport. They are amongst the most dynamic systems in the earth's surface and occur in all latitudes, in all climates, in all tidal ranges, and on all manner of coast. Beaches are at the top of the list of earth's natural attractions, drawling millions of visitors in all parts of the world (Pilkey et al. 2011).

Mexico has 11,122 km of coastline connecting its continental surface with the Pacific Ocean and the Gulf of California in the west, and with the Gulf of Mexico and Caribbean Sea in the east. Several regionalization have been proposed for their marine and coastal environments (Merino 1987; Rivera-Arriaga and Villalobos 2001; Ortíz-Pérez and De la Lanza 2006). According with Silva et al. (2014), sand beaches are the most noticeable feature of the Mexican littoral covering around 75% of the coast. For most of the national territory, shorelines are wave-dominated and microtidal (tidal range = 0–2 m). The beaches attract thousands of national and international visitors every year and support an important part of the Mexican economy through tourism and port activities as well as fisheries and aquaculture production.

Integrated coastal management can be defined as a continuous and dynamic process by which decisions are made for the sustainable use, development, and protection of the coastal and marine areas and resources. This process recognizes the distinctive character of the coastal area and the importance of conserving it for current and future generations (Cicin-Sain and Knecht 1998). The beaches, as a distinctive element of the coastal system, need specific tools for their planning and management.

This document seek to influence the strategic planning (geographic focused) and the operational planning (Kay and Alder 2005) of the Mexican beaches managerial process. To attain this goal, some coastal engineering tools will be presented in the next sections. All these tools were created to preserve and maintain the morphological character of the beaches and, where this is possible, to increase its sedimentary stability, but also, the use of these models contributes with the knowledge of the local beach dynamics, and could be used by coastal managers to take decisions in several phases of the planning or managerial process.

13.2 Methodology

Considering some of the general characteristics of the Mexican sand beaches (i.e. sediment size and composition; beach profile form and dimensions; location and extension) and the wave climatology (i.e. wave height and period) for the Pacific and Gulf of Mexico regions reported by Carranza-Edwards et al. (2004), Ortíz and De la Lanza (2006), and Silva et al. (2014), we sketch, for modeling purposes, an ideal tridimensional sand beach (Fig. 13.1).

This ideal beach was used to modeling its geomorphological stability by means of two simple approaches: (a) considering the longshore erosive potential associated with several wave heights and sediment size distribution and, (b) considering the cross-shore beach profile response associated with sea level rise during storm conditions.

Three conditions were used to simulate the beach behavior:

- Fine sediment size distribution: median sediment size D50 = 0.18 (mm) with Dmax = 0.29 (mm) and Dmin = 0.06 (mm)
- Median sediment size distribution: median sediment size D50 = 0.36 (mm) with Dmax = 0.58 (mm) and Dmin = 0.12 (mm)
- Mixed sediment size distribution: median sediment size D50 = 0.23 (mm) with Dmax = 0.55 (mm) and Dmin = 0.01 (mm)

Standard discrete simulation methods (Law and Kelton 1991) were used to simulate the sediment size distribution, and the results were validated with data from Srisuwan (2012) and Abuodha (2003). The beach profile response was obtained using the method proposed by Kriebel and Dean (1993), assessed with a theoretical model by Azuz (1999) and validated with information from Silva-Casarín et al. (2003) for the Quintana Roo region.

Regarding the beach management process, we stablished several phases in which the coastal manager can support their decisions on simple models that requires little field information or measurements (which is the case in many developing countries). Figure 13.2 shows the general diagram for the managerial procedure.

Phase 1 comprises the beach characterization as a dissipative, intermediate or reflective following some general parametrizations (dimensionless fall velocity and surf similarity parameter) and the classification proposed by Short (1999).

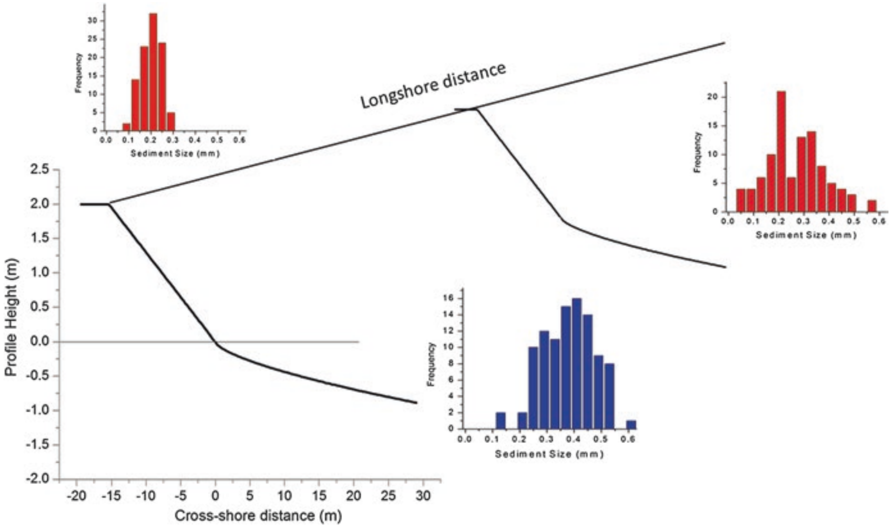
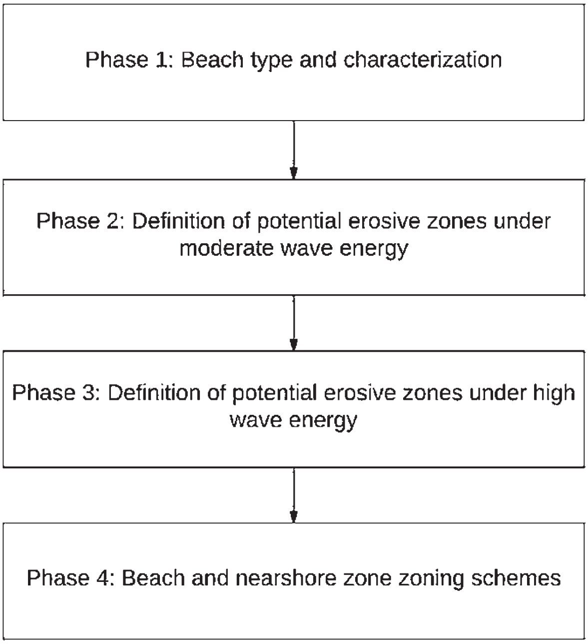


Fig. 13.1 Idealized 3D beach. Emerged part based on real data from Mexican beaches. Immersed part based on Dean's equilibrium profile form. Three different sediment distribution used in cross-shore and longshore dimensions. Vertical scale exaggerated

Fig. 13.2 Conceptual diagram about the beach managerial phases supported by simple morphodynamic models



Calculations was done for different sediment size distributions, beach profile shape and wave conditions.

In phase 2 potential erosive zones were established by means of the calculation of the critical wave high for sediment movement considering equilibrium beach profile form and several sedimentary and wave conditions. The maximum potential retreat for the beach profile was modeling (Kriebel and Dean 1993) under storm conditions as a part of phase 3 in order to define the potential erosive zones of the beach.

Finally, based on the global potential erosive risk for the beach (cross-shore and longshore directions) the coastal managers can create and deploy zoning schemes (phase 4).

All this elements need to be monitoring and evaluated under regular basis. We propose as a time framework a seasonal managerial structure. With four assessments per year, the beach could be managed in a proper way in terms of erosive risk, and we need to remember that the permanence of the physical structure of the beach is one of the most valuable resources for their visitors and users.

In the following section several variables, parameters and dimensionless numbers will be used. In the next lines we define those values that are common to the whole section. Specific parametrizations will be discussed in the corresponding subsections.

The density of sediment grains considered was: $\rho_s = 2650$ kg/m^3; the water density $\rho = 1023.3$ kg/m^3; the relative density of sediment $s = \rho_s/\rho = 2.59$; the kinematic viscosity of the water $\gamma = 9.43\times10^{-7}$ m^2/s (sea water temperature of 25° and salinity of 35 g/kg), and the acceleration of the gravity $g = 9.81$ m/s^2.

The dimensionless grain size (D_*) was defined as (e.g. Soulsby 1997):

$$D_* = D50\left[\frac{g(s-1)}{\gamma^2}\right]^{1/3}$$

In which $D50$ is the median grain diameter (m).

The Dean number (Suh and Dalrymple 1987) or dimensionless fall velocity (Ω) was defined as:

$$\Omega = \frac{H_b}{wT}$$

In which H_b = breaking wave height (m); w the settling velocity of the sediments (m/s) and T the wave period (s).

The Irribarren number or surf similarity parameter defined as:

$$\zeta = \frac{\tan(\beta)}{\sqrt{H_o / L_o}}$$

Where Tan(β) is the beach slope and H_o and L_o are the deep-water wave height (m) and length (m), respectively.

The settling velocity of natural irregular sand grains was calculated using the formula proposed by Soulsby (1997), valid for all D* and defined as:

$$Ws = \frac{v}{D50}\left[\sqrt{10.36^2 + 1.049D*^3} - 10.36\right]$$

In this paper, linear wave theory was used in all the calculations. To find the wave length (L) at intermediate depths, we solve the dispersion relation iteratively using the Steffensen method (Burden and Faires 1998) with the explicit wavelength formula proposed by Eckart (1951) as initial seed (Li), given by:

$$L = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi h}{L}\right) \quad with \quad Li = \frac{gT^2}{2\pi}\sqrt{\tanh\left(\frac{\sigma^2 h}{g}\right)}$$

In which $\sigma = 2\pi/T$ is the angular frequency in radian per second and h is the local water depth (m).

13.3 Beach Type and Characterization

Wave-dominated, micro-tidal beaches can be characterized as a: dissipative, intermediate or reflective according with their wave, sedimentary and morphologic properties (Short 1999; Masselink and Hughes 2003). Beach type can be predicted to some degree using the dimensionless fall velocity (Ω) and the surf similarity parameter (ζ). Reflective beaches occur when $\Omega < 1$ and $\zeta < 2.5$, which are associated with combinations of low waves and/or long wave periods with coarse sediments; narrow beach and swash zone with beach cusps are commonly presents. Intermediate beaches regularly present bars and rips and they occur when $1 < \Omega < 2$ and $2.5 < \zeta < 20$, and can be subdivided in: longshore bar and trough, rhythmic bar and beach, transverse bar and rip and low tide terrace. Finally, dissipative beaches occur when $\Omega > 6$ and $20 < \zeta < 200$; these beaches require fine sand and relatively high waves (moderate to high wave energy H > 1 m).

Using the long-term average (1948–2009) wave information (significant wave height and period) provided by Silva et al. (2014), for 20 locations covering the whole Mexican coast (Pacific, Gulf of Mexico and Caribbean Sea) we define the long-term mean type of beach. Local and temporary changes in this definitions are expected due to the dynamic nature of beach morphology. Figures 13.3 and 13.4 show the results obtained for the east and west coast. Regions 1–8 correspond to the east coast and the numeration goes from north to south; in the west coast 12 regions were analyzed (region 9–20). In general, long-term average significant wave height (Hs) goes from 0.88 to 1.75 m, and wave period (T) 3.81 to 6.68 s in the record used.

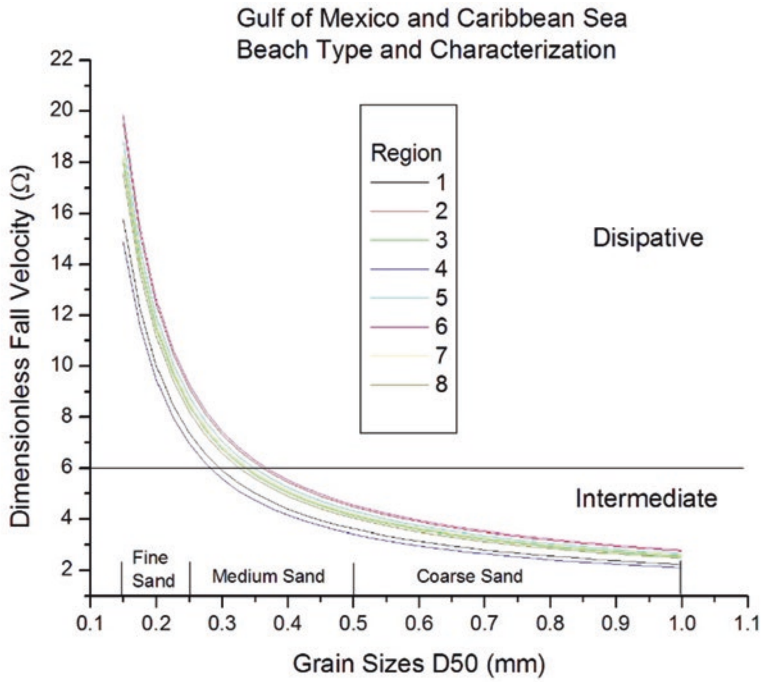


Fig. 13.3 Beach type according with the dimensionless fall velocity (Ω) and sediment size for the Gulf of Mexico and Caribbean Sea coast. The different color lines correspond to specific long-term average wave conditions defined for each region (Silva et al. 2014)

If we use the three theoretical sediment size distributions proposed in this study with D50 = 0.18 mm, D50 = 0.23 mm, and D50 = 0.36 mm, and the average conditions (Hs and T) for each coast, the characterization of the beaches can be observed in Table 13.1.

As a gross approach for beach management, these simple calculations could be useful to define better use conditions. Dissipative and intermediate beaches are more likely to be used as a recreational areas than reflective beaches; also spilling breaking (associate with dissipative topography) can be safer for swimmers and nearshore activities. In intermediate beaches, longshore bar-trough systems and rip currents could be dangerous for the users (swimmers, people playing in shallow zones, nautical activities, etc). Beach manager could stablish seasonal and site-specific (in the longshore direction) risk programs based on the local character and type of beach with a small amount of data and simple models.

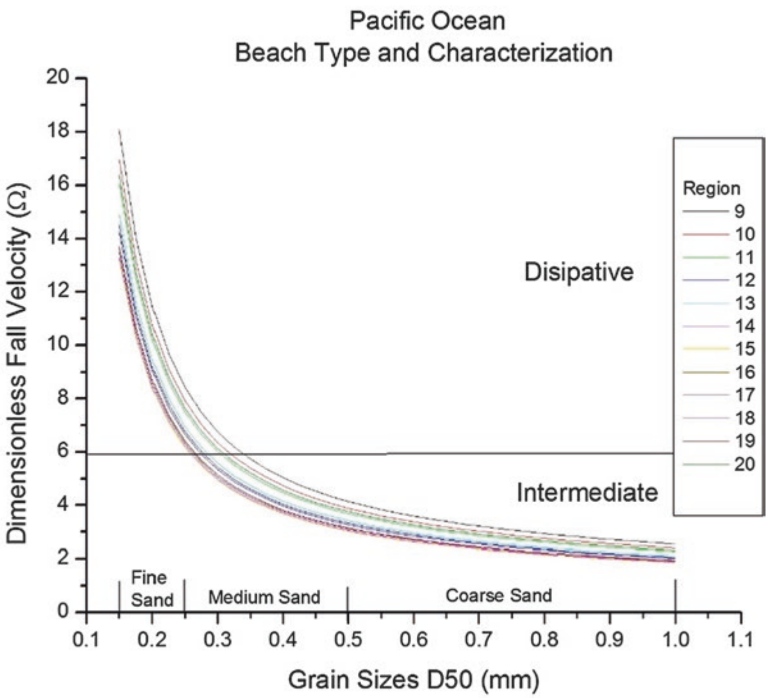


Fig. 13.4 Beach type according with the dimensionless fall velocity (Ω) and sediment size for the Pacific coast. The different color lines correspond to specific long-term average wave conditions defined for each region (Silva et al. 2014)

Table 13.1 Beach type and characterization according with the dimensionless fall velocity parameter (Ω) for the theoretical median diameters and long-term average wave conditions for the East and West coast

	East Coast		West Coast	
Sediment size D50 (mm)	Omega value	Beach type	Omega value	Beach type
0.18	13.4	Dissipative	11.1	Dissipative
0.23	9.4	Dissipative	7.7	Dissipative
0.36	5.5	Intermediate (longshore bar and trough beach)	4.6	Intermediate (rhythmic bar and beach)

13.4 Sediment Mobility and Potential Erosive Risk on Beaches under Moderate Wave Energy

Around the world, natural or human-induced erosive processes on sandy beaches is a matter of concern for coastal managers, researchers, stakeholders and users (Williams 2001; UNEP-GPA 2003; EUROSION 2004a, b; EC 2004; Camacho-Valdéz et al. 2008; Hegde 2010; Frihy et al. 2010; Morang et al. 2013; Aagaard and

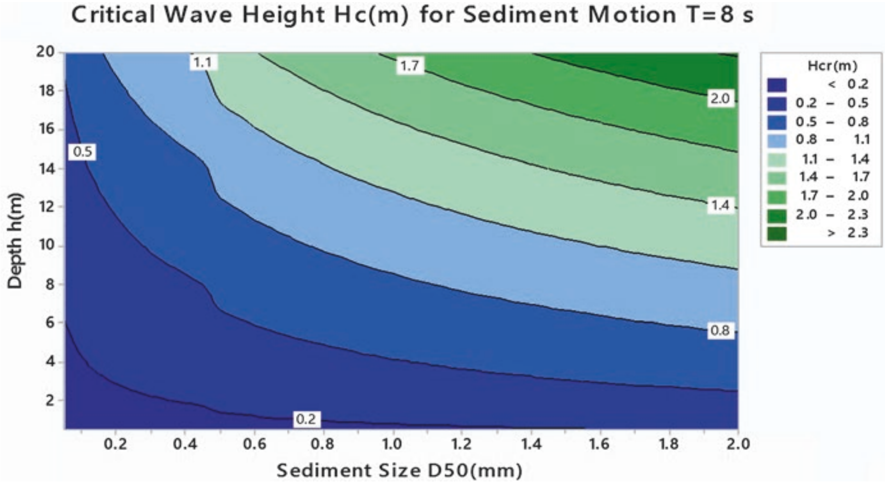


Fig. 13.5 Critical wave height for sediment motion at different depths with a T = 8 s period wave

Sorensen 2013; Palalane et al. 2016; Do Nascimento and Pereira 2016). Waves, tides, winds, longshore currents and accelerate sea level rise are the natural driving forces, magnified during extreme weather events. Human activities like dam construction or the installation of coastal defense and protection structures, many times produces strong erosive processes.

For many years, morphodynamics modeling has been a common practice in the coastal engineering arena to assess and predict the potential erosion on the beach, the bottom changes in the nearshore zone or shoreline changes (Komar 1983; Horikawa 1988; Van Rijn 1993; Silvester and Hsu 1993; Reeve et al. 2004). Following Gravois et al. (2016), a very general classification of morfphodynamic models could be defined:

- One-line shoreline models
- Multi-line shoreline models
- Conceptual equilibrium type models
- 2D process-based models
- 3D process-based models
- Statistical/probabilistic model

The use of these kind of models require a regular level of economic resources, by example to buy commercial software, and technical capacities to understand its operation, validate the model results or calibrate their parameter. Unfortunately, many times in developing countries coastal manager –if they exists- do not have these capacities. To overcome this obstacle a gross approximation to define potential erosive risk the principles of sedimentary mobility could be used.

The results presented in this section were derived considering the critical wave conditions to start the sediment movement. Using this information it is possible to

Table 13.2 Critical wave height (m) for sediment movement considering different sediment sizes and wave period (T) at 20 m depth

Theoretical sediment distributions	Sediment size in mm (Dmin, D50 and Dmax)	T = 6 s	T = 8 s	T = 10 s	T = 12 s
Fine	0.06	0.99	0.58	0.50	0.47
	0.18	1.42	0.84	0.72	0.68
	0.29	1.67	0.98	0.84	0.80
Medium	0.12	1.24	0.73	0.62	0.60
	0.36	1.80	1.10	0.90	0.86
	0.58	2.47	1.37	1.13	1.04
Mixed	0.01	0.54	0.32	0.27	0.26
	0.23	1.55	0.91	0.78	0.74
	0.55	2.42	1.34	1.10	1.01

define which areas on the beach and nearshore zone could be more susceptible to mobilize and in this way a erosive potential map could be stablished.

Figure 13.5 shows the critical wave height (Hc) needed to mobilize certain class of sediments under 8 s period waves. The equations used to build the graphic are based on the proposal from Komar and Miller (1973) which involve the calculations of the critical bed-shear stress and the pick value of critical the near-bed wave orbital velocity, according to linear wave theory (presented in and implicit way in this case):

$$Hc = \frac{T^{4/3}\sinh(kh)D50^{1/3}}{\pi}\left[0.118g(s-1)\right]^{2/3} \quad \text{for } D50 < 0.5\,\text{mm}$$

$$Hc = \frac{T^{8/7}\sinh(kh)D50^{3/7}}{\pi}\left[1.09g(s-1)\right]^{4/7} \quad \text{for } D50 > 0.5\,\text{mm}$$

All the variables used were defined in Sect. 13.2.

Considering the three sediment size distribution for the theoretical beach and assuming uniformity of the distribution across the beach profile, Table 13.2 shows the critical wave height needed to mobilize all the sediment classes.

Considering the results presented in Table 13.2, and supposing a theoretical beach with a non-uniform longshore gradation of sediment size distributions, from predominantly smallest sizes on one side (longshore beach limits) to large sizes in the other then, for a theoretical beach composed by fine sands (0.06–0.29 mm) a 1 m wave height and T = 8 s, could easily erode large part of the beach profile; considering the same wave it would be safer a medium size sand beach. We need to remark that the values showed in Table 13.2 consider the sediment movement at depths of 20 m at shallow waters the mobility need to be more intense. Whit this information coastal manager could stablish longshore and cross-shore maps of potential erosion under different wave conditions scenarios.

Table 13.3 Maximum beach retreat (Rmax) in meters for different sediment sizes under two storm conditions (Td = 8, 6 h and Hb = 3 and 4 m) and with a sea level rise of 1.5 m

Theoretical sediment distribution	Sediment size D50 (mm)	Td = 8 h		Td = 66 h	
		Hb = 3 m	Hb = 4 m	Hb = 3 m	Hb = 4 m
Fine	0.18	20	30	48	56
Medium	0.36	7	9	9	12
Mixed	0.23	10	20	31	38

13.5 Potential Erosive Risk on Beaches Under High Wave Energy

Since the beginning of the 60s and 70s the geometrical study of the beach profile response to sea level rise due to storms, storm surge and in general to energetic waves, has been a common practice in coastal engineering (Bruun 1962; Edelman 1968, 1970; Dean 1977). Based on the concept of equilibrium beach profile, different profile geometries, storm properties and sediment characteristics, Kriebel and Dean (1993) develop and validate with real data a simple method to predict –among other factors- the potential beach erosion (Vinf) and the maximum beach retreat (Rmax). The method, commonly refer as "convolution method" has been applied and used for comparison with other models, recently by Callaghan et al. (2008), Almeida et al., (2011), Ranasinghe et al. (2013) and Taborda and Ribeiro (2015) with good results according with the sophistication/simplicity of the model.

In this section we use the theoretical beach profile defined in Fig. 13.1, with a square berm (2 m high), a linear beach face slope (tan(β) = 0.13), and Dean's equilibrium profile for the immersed part of the profile according with the equation $h = Ax^{2/3}$, in which h is the local depth (m), x the cross-shore distance (m) and the sediment scale parameter A ($m^{1/3}$) giving by Dean and Dalrymple (2002). To evaluate the erosive risk of the theoretical beach by means of the maximum beach retreat (Rmax), we run the model with 3 different breaking wave heights (Hb = 3 and 4 m), a sea level rise of 1.5 m and storm duration (Td) of 8 and 66 h. The results are presented in Table 13.3.

Looking at the presented results (Table 13.3) the maximum potential beach retreat could occur in fine sand beaches, with a maximum value, according with the experimental setup, of 56 m. For coastal managers this information is very valuable. They can define medium to high risk areas in the upper part of the beach -for hurricane seasons- using the information of wave highs and sediment distribution in the longshore direction. The spatial zoning or risk plans should consider -giving the results of this kind of single models-, the safety distance to the sea for the installation of permanent (e.g. hotels, restaurants, recreational facilities, etc.) and temporary infrastructure (e.g. palapas, trash containers, etc.).

13.6 Conclusion

Three kind of models used in the coastal engineering practice has been presented, and the results inserted in a beach managerial framework. Starting as a first step with the definition of simple parameters to define the type and characterization of the beach, following by the evaluation of potential erosive zones using two methods (i.e. critical wave height calculations and maximum beach retreat) defined for regular and high wave energy, coastal manager could stablished spatial zoning plans for erosive risk on the beach.

All the proposed and evaluated methods for the theoretical beach conditions (observing the most general Mexican beach characteristics) need a minimum scientific knowledge or data availability (sediment size distributions, beach profile form, general wave climatology) to by applied. Considering the economic restrictions in developing countries and the technical and scientific limitations that regularly have the decision-makers and coastal managers, this could be a first step toward a more elaborated managerial practice.

This document attempts to give some technical elements and methodological paths to joint two often separated disciplines in many countries –like Mexico-, the coastal engineering –mostly associated with the academic research- and the coastal management –frequently located in the governmental arena-, using as a guiding line the erosive potential of the beach. The selection of this analytic element obey the fact that the main attraction of the beaches is the beach itself (form, extension, recreations qualities, etc.), and the principal function of coastal managers and engineers is preserve it for the enjoyment of present and future generations.

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