

## Beach Profiles and Cross-Shore Sediment Transport

*Although nature begins with the cause and ends with the experience, we must follow the opposite course, namely, begin with the experience and by the means of it investigate the cause.*

Leonardo da Vinci, 1452–1519  
*Notebooks*

An important aspect of a beach is its dynamic personality—the loose granular sediment continuously responds to the ever-changing waves and nearshore currents. The beach may achieve an equilibrium morphology in a laboratory wave tank where waves of constant height and period are maintained, but on natural beaches the changing wave and tide conditions give rise to an elusive equilibrium that the beach attempts to achieve but seldom does. However, the best way to understand beach profiles is in terms of a quasi-equilibrium and how it is determined by the waves, tides, and beach sediment. Ultimately, a full understanding depends on our knowledge of the processes of cross-shore sediment transport and on our ability to model the changing beach morphology using that knowledge.

In this chapter we will examine what is known about beach profiles: How sand shifts from the dry beach to the offshore and back again; why gravel beaches are steeper than sand beaches; what governs the number of offshore bars; and what are the effects of tides or a storm surge. Models and experimental studies of cross-shore sediment transport will also be reviewed in an attempt to understand the processes involved in beach profile development. For the most part, this chapter takes a two-dimensional view of the beach, the simple profile and the cross-shore sediment transport responsible for profile shifts in response to changing wave conditions. Although there will be some consideration of the third dimension of the beach—longshore variations in profile shapes—these will be considered in more detail in Chapter 11, where we examine rhythmic shoreline features such as crescentic bars and beach cusps.

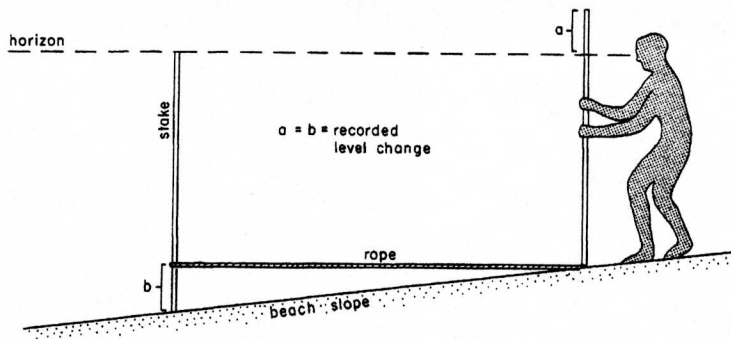
The beach profile is important in that it can be viewed as a natural mechanism that causes waves to break and dissipate their energy. Waves can reach the coast with a tremendous amount of power, having the potential to bring havoc to communities. Faced with increased waves, the beach responds by reducing its overall slope, shifting the breaker zone farther offshore, thereby enhancing the dissipation of the waves before they reach the shore. This flattening of the beach under storm attack must not be confused with erosion, which implies a permanent loss of foreshore material. Instead, with such an altered slope, the beach can better act as a buffer, protecting sea cliffs and coastal properties from the intense wave attack and thereby preventing true erosion. The ability of a beach to adjust itself to the prevailing forces makes it an effective method of coastal defense.

## THE MEASUREMENT OF BEACH PROFILES

Measuring beach profiles is more challenging than it might at first seem. This is particularly the case if the profile is to extend out through the breaker zone and into the deep water of the offshore. A variety of approaches have been taken to obtain complete profiles across the nearshore zone.

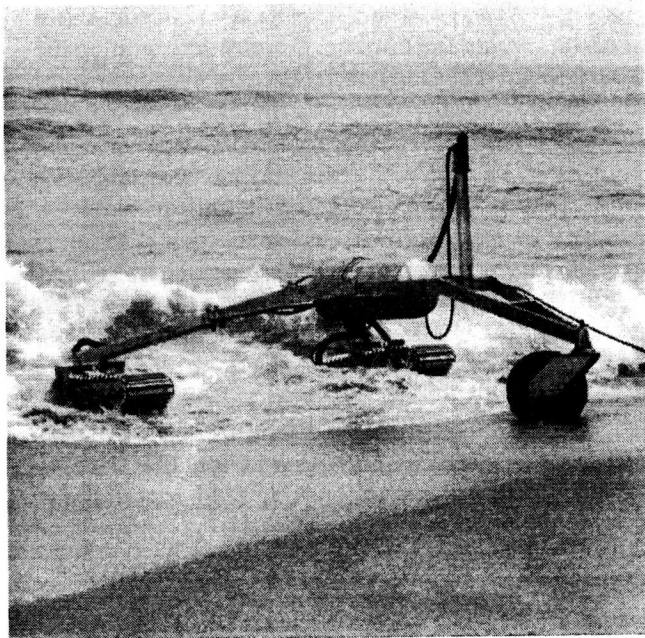
The measurement of most beach profiles involves standard practices of surveying with a rod and transit. This is a routine operation, except perhaps for the person holding the rod who must wade out into the breakers—the approach is obviously limited to the depth to which a tall student can safely wade. A low-tech variation involves use of the so-called “Emery boards,” first devised by K. O. Emery (1961). As depicted in Figure 7-1, the apparatus consists of two flat boards connected by a rope having a standard length such as 5 or 10 m, which determines the measurement interval along the profile. Each board has a scale running its length, with 0 at the top. If the beach is sloping downward toward the sea, the procedure is to sight across the top of the seaward board to the level of the horizon, thereby determining the distance  $a$  from the top of the landward board (Fig. 7-1). If the beach is locally sloping upward in the offshore direction, then  $a$  is measured on the seaward board and the sighting is with the horizon over the top of the landward board. In either case, the measured distance  $a$  is equal to the distance  $b$  that the beach has either dropped or risen within the horizontal distance between the boards (the rope length). Although this approach may seem crude, it can provide a reasonably accurate measure of profile elevations. Its advantages are that the equipment is inexpensive, light, and easily carried to distant survey sites, and the profiles can be obtained very quickly. Some studies have required the collection of a large number of profiles along the length of a beach, all obtained during the hour close to low tide; Emery boards make this possible, as their use is significantly faster than employing a rod and transit.

The portion of the profile in water depths too deep to wade in can be measured with a fathometer on a boat. However, there is usually a considerable degree of inaccuracy in the measured depths due to the combined effects of waves, tides, and other factors that may alter water levels. There are additional problems in accurately establishing the horizontal position of the boat at all times during the profiling operation.

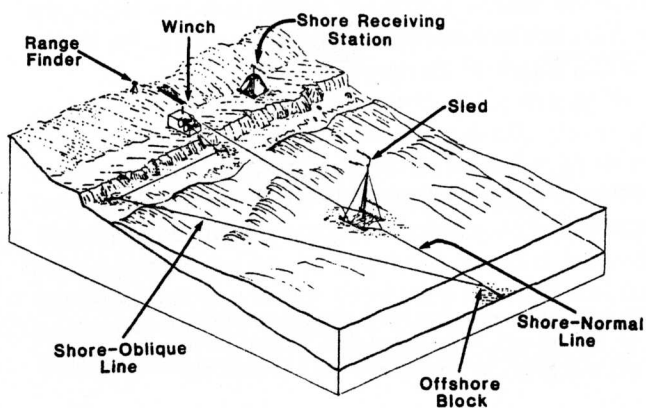


**Figure 7-1** The “Emery board” apparatus for measuring beach profiles, consisting of two wooden boards marked from the top with rulers to measure the distance  $a$ , which is equal to the beach elevation change  $b$ . The length of the rope controls the measurement interval.

Some success has been achieved in developing vehicles that can obtain beach profiles that extend across the entire nearshore and into deep water. Seymour, Higgins, and Bothman (1978) and Dally, Johnson, and Osiecki (1994) have designed remotely controlled tractors. Figure 7-2 shows the Surf Rover of Dally and co-workers, which can be folded up and transported by truck. The tractors are run by electric motors with onshore sources of power delivered through umbilical cords. The horizontal position as well as vertical profiles are obtained from on-board instrumentation, all self-contained under water, and the data are immediately transmitted back to shore through the cable. Sallenger et al. (1983) have developed a sled that is towed across the surf zone with a winch and system of lines (Fig. 7-3). The sled is large and massive—5.5 m long, 4 m wide, and weighs approximately 800 kg (1800 lbs) including ballast. With this mass and size, the sled can be used under high wave conditions. The triangular line system makes it possible to tow the sled with the winch in either the onshore



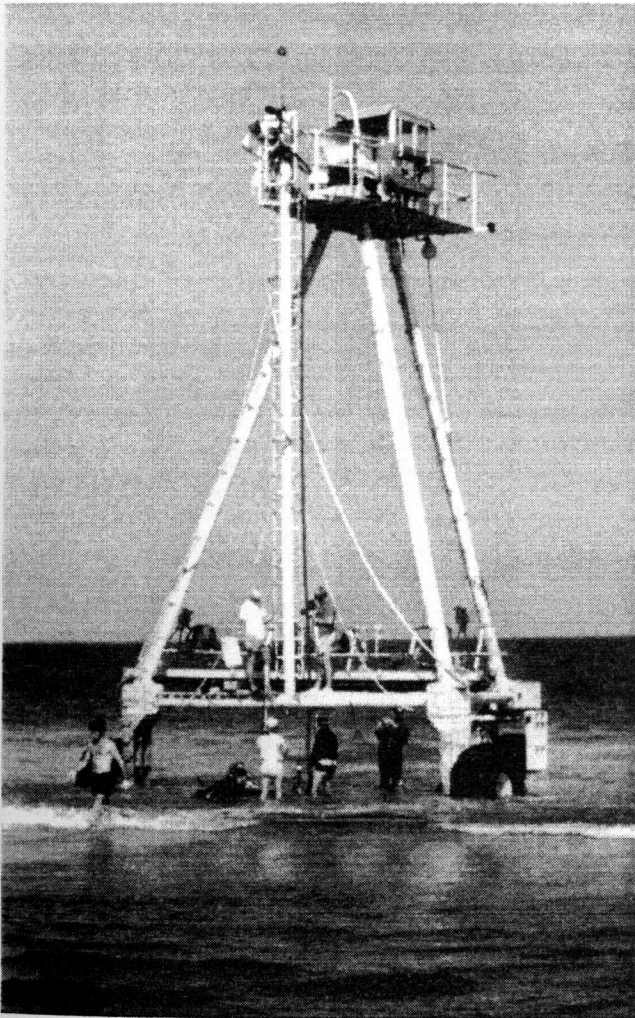
**Figure 7-2** The amphibious Surf Rover that can be used to survey the morphology of a beach. The vehicle is 7-m long, 5-m wide, and 1.5-m high, and its nominal dry weight is 1,360 kg (3,000 tons). [Used with permission of Marine Technology Society, from W. R. Dally, M. A. Johnson and D. A. Osiecki, Initial Development of an Amphibious ROV for Use in Big Surf, *Marine Technology Society Journal* 28. Copyright © 1994 Marine Technology Society.]



**Figure 7-3** The use of a massive sled to measure beach profiles, the system of lines allowing it to be moved in either direction across the beach. [Reprinted from *Marine Geology* 51, A. H. Sallenger, P. C. Howard, C. H. Fletcher, and P. A. Howd, A System For Measuring Bottom Profile, Waves and Currents In the High-energy Nearshore Environment, p. 65, 1983 with kind permission of Elsevier Science-NL, Sara Burgerhartstratt 25, 1055 KV Amsterdam, The Netherlands.]

or offshore directions. The sled contains a steel mast with three optical prisms mounted at the top. An infrared range finder on the dry beach measures the slope distance to these prisms, which yields the horizontal and vertical distances in the cross-shore profile.

An innovative vehicle for measuring beach profiles is the Coastal Research Amphibious Buggy (CRAB) used at the Field Research Facility (FRF), Duck, North Carolina (Birke-meier and Mason, 1978). The CRAB, (Fig. 7-4) is a 10.6-m high motorized tripod that can survey the surf zone out to depths of 9 m. Power is supplied by a Volkswagen engine, and its top speed is 2.5 mph (4 km/hr) on land and somewhat less in water. Although it looks top heavy, the liquid-filled tires and wide wheel base provide excellent stability (the design overturning angle is  $45^\circ$ ). Surveying utilizes an automated tracking device that aims at a prism cluster mounted on the CRAB and then measures the distance to the CRAB together with the horizontal and vertical angles; a micro-processor calculates the X, Y, and Z coordinates and stores them in memory. Based on repetitive measurements of the same profile, the vertical and horizontal accuracy are placed at  $\pm 3$  cm. The operation requires only two people (vehicle and



**Figure 7-4** The CRAB, consisting of a 10.6-m tall tripod run with a Volkswagen engine, used to measure beach profiles at the Field Research Facility of the Coastal Engineering Research Center at Duck, North Carolina. [Courtesy of R. Holman]

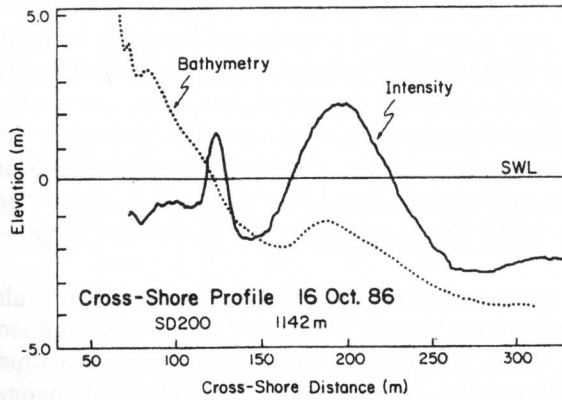
instrument operators), a considerable savings in personnel and time compared with standard surveying techniques. The only significant drawback of the CRAB is its lack of portability.

An unusual "remote sensing" technique has been developed by Holman and Lippmann (1986) and Lippmann and Holman (1989) to investigate beach profiles, in particular, the locations and forms of offshore bars. The technique is based on the patterns of wave breaking in the nearshore, which are determined mainly by the shallower water of the bars. As illustrated in Figure 7-5(a), a snapshot of wave breaking at some instant in time is suggestive of the presence of a sand bar, but the poor spatial coverage provided by the breaking wave crests and the statistical uncertainty associated with time variations in the sizes of the waves make the details of the bar unclear. However, a 10-minute time exposure [Figure 7-5(b)] yields a much clearer view of the pattern of wave dissipation and hence of the bar form. The long exposure time averages out the fluctuations of the individual waves and gives a statistically stable image of the wave dissipation and bar topography. The record for such an analysis can be obtained with an ordinary camera set for a time exposure, but more advanced techniques utilized by Holman and Lippmann employ a record from a video camera that is analyzed with a computer. A time exposure is obtained by summing successive images, and it is also possible to use differencing (the subtraction of consecutive frames) to remove residual foam from the images.



**Figure 7-5** Oblique video images of the nearshore at the Field Research Facility, Duck, North Carolina. (a) A snapshot shows the instantaneous patterns of wave breaking that are suggestive of the beach bathymetry, particularly the presence of an offshore bar. (b) A 10-minute time exposure yields a white band in the offshore from many occurrences of wave breaking, showing the outlines of the bar and a zone of wave dissipation due to swash on the beach face. [Used with permission of American Geophysical Union, from T. C. Lippmann and R. A. Holman, Quantification of Sand Bar Morphology: A Video Technique Based on Wave Dissipation, *Journal of Geophysical Research* 94, p. 996. Copyright © 1989 American Geophysical Union.]

Lippmann and Holman (1989) tested their imaging technique at the FRF in Duck, North Carolina. In that specific experiment, a Panasonic black-and-white video camera was mounted on top of a 40-m high tower, erected on the dune crest immediately behind the beach. The recorded wave dissipation due to breaking was used to infer the bar position and form, which was then compared with actual beach profiles measured with the CRAB. An example is shown in Figure 7-6 where the intensity values determined from the video are non-dimensional with absolute magnitudes that reflect the bathymetry of the beach. There is a clear maximum in the intensity distribution that corresponds to the location and general form of the bar. A second maximum in the intensity occurs on the beach face due to the swash turbulence; the position of the peak intensity was found to coincide with the shoreline, defined as the intersection of the still-water level with the beach face. Figure 7-7 demonstrates



**Figure 7-6** The correspondence between the cross-shore intensity of wave dissipation measured with the video-imaging technique and the bathymetry of the beach profile. [Used with permission of American Geophysical Union, from T. C. Lippmann and R. A. Holman, Quantification of Sand Bar Morphology: A Video Technique Based on Wave Dissipation, *Journal of Geophysical Research* 94, p. 1003. Copyright © 1989 American Geophysical Union.]



**Figure 7-7** Crescentic bars outlined by the patterns of breaking waves, recorded with a 10-minute time exposure using the video-imaging system. [Used with permission of American Geophysical Union, from T. C. Lippmann and R. A. Holman, The Spatial and Temporal Variability of Sand Bar Morphology, *Journal of Geophysical Research* 95, p. 491. Copyright © 1990 American Geophysical Union.]

the ability of the technique to record the spatial patterns of bars, in this case an example of well-developed crescentic bars (Chapter 11). Lippmann and Holman (1990) obtained such images daily for 2 years at FRF in order to investigate how the bars respond to storms. It is under such conditions that their imaging technique is of greatest value, as the bar evolution is rapid and traditional survey methods and even the CRAB cannot be used during major storms. Their results will be examined in Chapter 11 where we will consider the three-dimensionality of beach morphology and how it changes under varying wave conditions.

## GENERAL BEACH MORPHOLOGY AND VARIATIONS

Figure 7-8 contains examples of beach profiles from various coastal sites as well as from a laboratory wave channel. In most of these examples the profiles are graphed with extreme vertical exaggerations that make the bars appear more pronounced than they actually are and the beach face substantially steeper. Such vertical exaggerations help to emphasize the subtle variations in profiles but care must be taken to not be misled by the distortion. The series in Figure 7-8 illustrates the usual components of beach profiles, including the sloping beach face, the possible presence of a berm, and the common existence of one or more bars with intervening troughs. There is already some hint of the factors that control the profile morphology, such as the sediment grain size determining the beach-face slope—these factors will be explored below.

The collection of repeated surveys at a site, spanning months to years, generally reveals an envelope of profile variations. This is illustrated by Figure 7-9 containing profiles obtained at the FRF in North Carolina (Birkemeier, 1984). The vertical variations are greatest within the nearshore, particularly where bar-trough systems develop, with the envelope of change thinning and pinching out toward the offshore. Hallermeier (1981) has examined this zonation and attempted to relate it to the annual wave climate. The *closure depth*,  $h_c$ , the limit of the zone of extreme bottom changes for quartz-sand beaches, was found to be given approximately by

$$h_c = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right) \quad (7.1)$$

where  $H_e$  is the nearshore storm-wave height that is exceeded only 12 hours per year, and  $T_e$  is the associated wave period. This in effect is a dependence on the wave height, with an adjustment for the wave steepness. Birkemeier (1985) has compared this relationship with profile variations at the FRF and found that a replacement of the coefficients in Equation (7.1) with the values 1.75 and 57.9 yields a better fit to the data. Birkemeier also noted that the simple proportionality  $h_c = 1.57H_e$  provides a satisfactory prediction of the closure depth.

Although beach profiles can be complex due to a series of bars and troughs, in general they are steepest at the shore and have a progressively decreasing slope as the water depth increases in the offshore direction. This regularity has inspired attempts to develop mathematical expressions to describe the profile shape. These formulations can then be used in analyses of wave dynamics during shoaling, in examinations of the generation of nearshore currents and sediment transport, and in computer models of beach morphology evolution and shoreline change. The beach profile expression that has seen most common use in engineering applications is that derived by Bruun (1954) and Dean (1976, 1977, 1991),

$$h = Ax^{2/3} \quad (7.2)$$