Figure III-5-8. A mud 'beach' backed with eroding salt marsh at Annapolis Royal, in the Annapolis Bay of the Bay of Fundy. Basalt revetment at top of salt marsh is an attempt to halt the erosion

(3) Mangrove. Tropical coastal wetland where the vegetation, in the form of trees, can withstand relatively severe wave attack (Figure III-5-9). Depth-limited waves will penetrate a mangrove, eroding mud from around the root system in extreme storms, and endangering individual trees. Mangrove can be found between mud flats and salt marsh, and can transmit waves, which erode the adjacent salt marsh behind it.

(4) Mud 'beach.' A sloping mud shore, exposed to wave attack often following the destruction of mangrove or other wetland vegetation (Figure III-5-8). The usual cause of wetland or mangrove destruction is property developers, municipal agencies, and individuals wishing to 'reclaim' the shore. Natural destruction occurs from the seaward edge, through undermining of the root system by waves and currents.

III-5-3. Erosion Processes on Consolidated Shores

a. Erosion processes on cohesive shores are distinctly different from those on sandy shores. There are also differences between consolidated and mud cohesive shores. On consolidated shores, the erosion process is irreversible because, once eroded, the cohesive sediment (e.g., glacial till, glacio-lacustrine deposits, ice bonded sediments, soft rock or other consolidated deposits) cannot be reconstituted in their consolidated form in the energetic coastal environment. Furthermore, since the sand and gravel content is low in these deposits (often less than 20 percent), erosion is not balanced by an equal volume of deposition within the littoral zone. The eroded fine sediments (silt and clay) are winnowed, carried offshore, and deposited in deep water in contrast to the sand fraction, which usually remains in the littoral zone.

Figure III-5-9. Sand beach disappearing into mangrove on the island of Borneo. Sediment within the mangrove is cohesive mud

b. Consolidated cohesive sediment is eroded by at least four mechanisms:

(1) Through abrasion by sand particles moved by waves and low currents.

(2) Through pressure fluctuations associated with turbulence generated at various scales such as wave-breaking-induced turbulence that reaches the lake or seabed and large-scale eddies that may develop in the surf zone.

(3) Through chemical and biological influences.

(4) Through wet/dry and freeze/thaw cycles where exposed to the atmosphere.

c. Sand can also provide a protective cover to the underlying cohesive substratum. However, only when the sand cover is sufficient to protect the cohesive substratum at all times will the shore revert to a sandy classification (i.e., truly a 'thick pile of sand').

d. On consolidated cohesive shores, the rate of lake or seabed downcutting determines the long-term rate at which the bluff or cliff retreats at the shoreline. In other words, while subaerial geotechnical processes may dictate when and where a slope failure will occur, the frequency of failures over the long term is determined by the rate at which the nearshore profile is eroded (i.e. the downcutting rate). Subaqueous and subaerial erosion processes on cohesive shores are discussed in detail in Part III-5-7. In addition, the geomorphology of cohesive shores and the relationship to erosion processes is the topic of Part III-5-5.

III-5-4. Physical and Numerical Modeling

a. Laboratory or physical model experiments have been used in two ways: (1) to improve the understanding of the fundamental principles of cohesive shore erosion processes, and (2) to develop a measure of the erodibility of specific samples of cohesive sediment.

b. In the former category, scale model tests have been performed in wave flumes as described by Sunamura (1975, 1976 and 1992) for erodible rocky coasts similar to consolidated cohesive behavior, by Nairn (1986) for a section of the Lake Erie shoreline using an artificial clay, and by Skafel and Bishop (1994) and Skafel (1995) using intact samples of till removed from the Lake Erie shoreline. The tests described by Skafel and Bishop (1994) included an assessment of the relationship between wave properties (e.g., wave height, orbital velocity, type and fraction of broken waves) and local erosion rate and the relationship between sand cover and erosion rates. Laboratory experiments on erosion and deposition of mud are described in Part III-5-6c(9). The annular flume, used in both the laboratory and the field (e.g., Amos et al. 1992, Krishnappan 1993) may be regarded as a full-scale model of the response of a mud bed to shear.

c. The primary difficulty in the use of physical model experiments of cohesive shores is the scaling of the cohesive material. At present, it is not possible to accurately scale cohesive sediment with respect to its erosion resistance properties. Therefore, model tests must be interpreted qualitatively, or full-scale tests must be conducted using low wave energy conditions. Nevertheless, the noted tests have been extremely valuable in advancing the understanding of cohesive shore erosion processes both inside and outside the surf zone.

d. A technique of assessing the erodibility of intact samples of consolidated cohesive sediment in unidirectional flow conditions has been developed and applied by Kamphuis (1990), and, more recently, for the assessment of cohesive sediment samples removed from the southeast shoreline of Lake Michigan (Parson, Morang, and Nairn 1996). These tests are typically performed for both clear water and sand in flow conditions to elucidate the importance of sand as an abrasive agent. This approach for defining the erodibility of cohesive sediment samples is discussed in more detail in Part III-5-7b.

e. The development and application of numerical models for describing erosion processes on cohesive shores is not far advanced owing to the complexity of the processes involved. Most numerical models may be described as little more than numerical frameworks for interpolating or extrapolating observed behavior of cohesive sediments in water. Essentially, a numerical model of cohesive shore erosion must define the near-bed flow conditions within the surf zone, the movement of any overlying noncohesive sediment cover, as well as the erosion resistance properties of the cohesive sediment (which change with time due to exposure of sediment layers and subaerial drying). Numerical modeling of cohesive shores is summarized in Part III-5-12.

f. The best 3-D numerical mud models (e.g. Le Hir 1994) treat the water column as a continuum: from stationary consolidating bed, through fluid mud, to sediment maintained in suspension by turbulence. There are nevertheless bed sediment 'modules,' which use the equations presented in Parts III-5-7, 9, and 10 to calculate erosion and deposition, supplying sediment and new bathymetry to numerical hydrodynamic models that transport the sediment by advection and dispersion (Part III-5-8a).

g. All mud models need to track sediment layering - the composition and state of each sediment layer at each grid point in the model — more a bookkeeping function than numerical modeling.