CHAPTER ONE HUNDRED THIRTY FOUR

CROSS-SHORE TRANSPORT OF BIMODAL SANDS

Bruce M. Richmond* and Asbury H. Sallenger, Jr.*

ABSTRACT

Foreshore sediment level and sediment size were monitored as part of an extensive nearshore processes experiment - DUCK 82. Changes in foreshore texture were compared with computed values of onshore transported material based on current measurements from the surf zone and sediment transport theory (Bagnold, 1963, 1966). Preliminary results indicate reasonable agreement between predicted size of sediment transported onshore and beach texture changes. It is also demonstrated that coarse sediment may move onshore while finer material may simultaneously move offshore.

INTRODUCTION

Theoretical (Bowen, 1980) and field (Murray, 1967) studies have shown the possibility of oppositely directed sediment transport for different sized material under oscillatory flow. As waves shoal, oscillatory water velocities become asymmetric with a strong landward flow followed by a slower and longer seaward return flow. Because of its higher peak flow, the landward-directed current is able to transport coarser material than the seaward current. Zenkovich (1967) discussed a hypothetical situation where 1 mm diameter particles were in equilibrium with the local conditions. Particles finer than 1 mm moved seaward while coarser particles moved landward with particles of 4 mm diameter having the greatest landward thrust. In a tracer study using three different particle sizes, Murray (1967) demonstrated under conditions of shoaling wind waves that finer grain sizes had a greater tendency to move offshore. Bowen (1980) showed theoretically that when a sediment of a given grain size is in equilibrium with a given slope and wave regime (net sediment transport rate is zero for this size) any coarser material should move onshore and finer material offshore.

Sonu (1972) working at Nags Head, N.C. described variations of foreshore profile and beach sediment texture over a period of several months. He discussed a sequence of texture changes associated with storm and recovery cycles which can be summarized as follows: a) The passage of a storm resulted in a foreshore composed of unimodal fine sediment. b) In the early stage of beach recovery, coarse material with a unimodal distribution appeared in the lower foreshore.

* U.S. Geological Survey, Menlo Park, CA 94025

c) Continued accretion was accompanied by the addition of finer material leading to a strongly bimodal sediment composition. d) At the well-developed accretive state, finer sands were the dominant beach sediment. Sonu proposed that the length of time for the above cycle to occur was on the order of 2-3 months.

In this paper, we present field data from the Outer Banks of North Carolina on beach profile and sediment texture changes. This study was in conjunction with other studies on surf-zone processes during the DUCK 82 experiment (Mason and others, this volume). The experiment site at the Field Research Facility (FRF) of the U.S. Army Coastal Engineering Research Center at Duck, N.C. offered an excellent opportunity to examine mobility of different grain size populations under a variable wave climate. A wide range of sediment sizes is present including a terrigenous (non-biological) pebble fraction (Figure 1). We compared measured foreshore grain size to grain-sizes predicted to move onshore by a sediment transport model (Bagnold, 1963, 1966; Bowen, 1980).

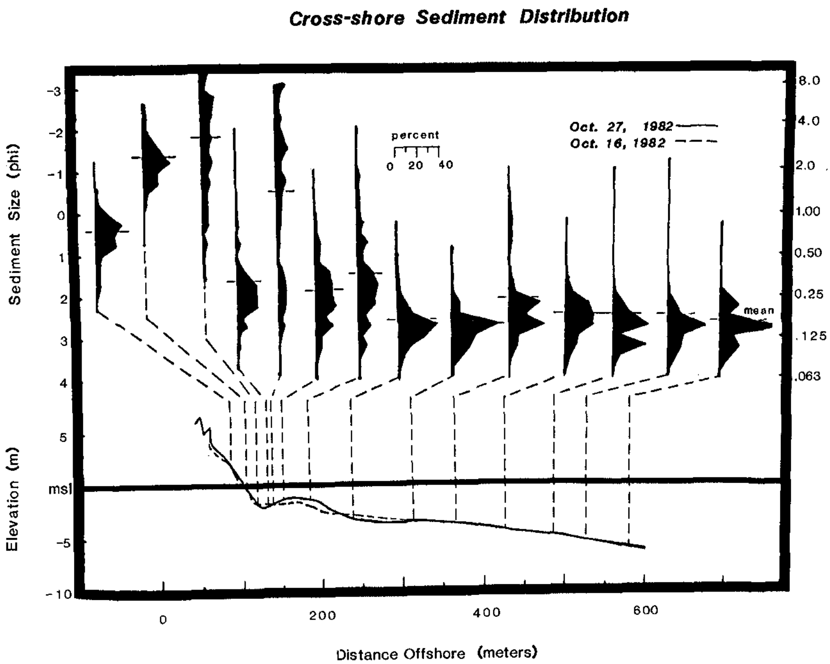

Figure 1. Cross-shore sediment distribution along the USGS sled line.

EXPERIMENT DESIGN AND METHODS

The data collection effort involved sampling foreshore sediments and measuring sediment-level variations while gathering nearshore wave and current measurements (Figure 2). Foreshore sediment levels were measured relative to the tops of 1-cm-diameter aluminum rods spaced 2.5 m apart in a shore-normal line. This line was part of a 35 by 40 meter foreshore grid described more fully in Howd and Holman (this volume). Uniform foreshore sand samples 6 mm thick were collected by a "cheese-slicer" device while beach gravels were hand sampled. Offshore samples were obtained with a grab sampler deployed from the CRAB (Coastal Research Amphibious Buggy). Foreshore sediment and sediment levels were monitored at variable intervals depending on the beach response and the goals of a particular experiment, although measurements were made at least daily.

Twice-daily nearshore profiles were obtained with the USGS sled system (Sallenger and others, 1983). Electro-magnetic flow meters attached to the sled provided current information. The data were telemetered to a shore receiving station. The length of each data run was 34.1-minutes (see Sallenger and Holman, this volume).

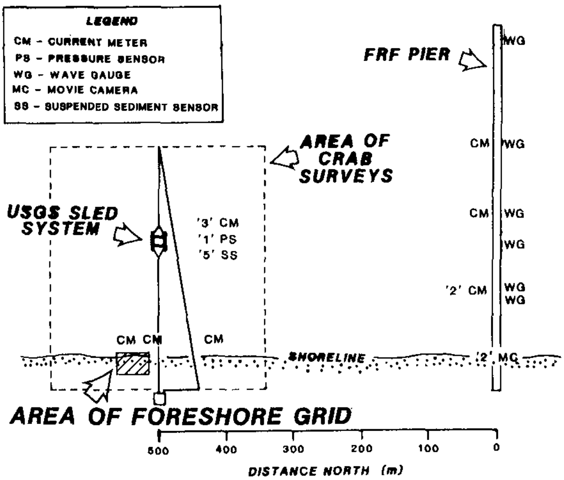

Figure 2. Map showing experimental set-up for the DUCK 82 experiment. The foreshore grid is 35 by 40 meters (it is discussed more extensively in Howd and Holman, this volume). FRF=Field Research Facility, CRAB=Coastal Research Amphibious Buggy. The USGS sled is not drawn to scale.

Calculation of Sediment Transport

Although the mechanisms of sediment transport and deposition on the beach face differ from those in the nearshore, the sediment moving onshore through the inner surf zone should be an indicator of the material deposited on the foreshore. Bagnold's (1963, 1966) total-load transport model was used to predict at which grain size a reversal in transport direction would occur at an inner surf-zone station close to the swash zone. The reversal size is that size at which coarser material should move onshore and finer material offshore. These predictions were compared with actual changes of foreshore grain size. Bagnold's model was selected because it has been used successfully to explain some characteristics of cross-shore sediment transport (Bowen, 1980).

From Bowen (1980), the total immersed weight transport is

$$\dot{i}_t = \dot{i}_s + \dot{i}_b \tag{1}$$

where the suspended load equals

$$\dot{i}_s = \frac{\epsilon_s C_D \rho u^3 |u|}{W - u\beta} \tag{2}$$

and the bedload is given by

$$\dot{i}_b = \frac{\epsilon_b C_D \rho u^3}{\tan\Phi - \dfrac{u\beta}{|u|}} \tag{3}$$

These equations were simplified as follows:

$$\dot{i}_s \approx \frac{\epsilon_s C_D \rho}{W}\left(\overline{u^3 |u|} + \frac{\overline{|u^5|}\beta}{W}\right) \tag{4}$$

$$\dot{i}_b \approx \frac{\epsilon_b C_D \rho}{\tan\Phi}\left(\overline{u^3} + \frac{\overline{|u^3|}\beta}{\tan\Phi}\right) \tag{5}$$

$$\dot{i}_t \approx C_D \rho \left(\frac{\epsilon_s}{W}\overline{u^3 |u|} + \frac{\epsilon_s}{W^2}\beta\,\overline{|u^5|} + \frac{\epsilon_b}{\tan\Phi}\overline{u^3} + \frac{\epsilon_b}{\tan^2\Phi}\beta\,\overline{|u^3|}\right) \tag{6}$$

Where:

C_D - drag coefficient (0.005; Bowen, 1980), i_t - total immersed-weight transport rate of solids, i_s - suspended-load transport rate, i_b - bedload transport rate, u - instantaneous cross-shore velocity (from sled measurements), W - fall velocity of sediment grains (variable), β - local slope (variable), ϵ_s - efficiency of suspended-load transport (0.025; Bailard, 1981), ϵ_b - efficiency of bedload transport (0.21; Bailard, 1981) ρ - fluid density ($1027.0 \frac{kg}{m^3}$), tan Φ - friction angle of sediment (0.63).

Input velocities were derived from a current meter at a height of one meter above the bed and local slope was measured from the sled profile taken nearest in time to the current measurements. Sediment settling velocity was varied at 0.005 m/s increments to determine at which "size" a reversal in sediment transport direction would occur.

RESULTS

Two data sets are discussed; the first considers foreshore texture changes for ten different days in October 1982, and the second examines nearshore profile and texture changes during a storm on Oct. 12th.

In the first example mid-foreshore sediment size was compared to the predicted size of sediment moving onshore past the landwardmost sled position for ten different days (Table I). In all cases the landwardmost sled position was immediately seaward of the swash zone. Significant wave heights determined from a waverider buoy in 18 meters of water three km from shore varied from a low of 0.7 m to a high of 2.3 m. In all cases the beach modal sizes were greater than or equal to the calculated values. Modal size is used because it corresponds to the most frequently occurring particle diameter and represents actual size of sediment present (mean grain size may be a size that is poorly represented in a bimodal sample).

Decreasing wave height was associated with a coarsening of the beach sediments and, conversely, increasing wave heights were followed by a fining of the foreshore. The initial coarsening may be due to the high mobility of the coarse sediments and close proximity to the probable source - the nearshore trough (Figure 1). The predicted reversal size is generally smaller than the actual foreshore sediment size which is consistent with the model because the calculated size represents the finest size which should be moving onshore. This is readily apparent on Oct. 14th where the predicted reversal size is 0.08 mm and the actual middle foreshore size is 4.1 mm. Finer material however, was deposited higher on the foreshore. It should be noted that there is a natural size grading across the foreshore, generally from coarse to fine as one travels landward across the foreshore, which accounts for some differences between observed and predicted sizes. Although only one sample per day is used in this analysis, there were samples periodically taken at 5 m intervals across the foreshore which confirmed the general fining or coarsening trends reported.

Table I. Variation between predicted and observed (two values indicate a bimodal sample) sediment changes.

Date/1982	Modal Mid-foreshore Sediment Sizes (mm)	Predicted Reversal Size* (mm)	Significant Wave Height (m)
10-10	0.35	0.36	2.2
10-11	0.42	0.36	2.3
10-12	0.71 0.30	0.38	2.1
10-13	1.41	0.39	1.6
10-14	4.10	0.08	1.1
10-15	0.71	0.18	0.7
10-17	0.35	0.08	1.5
10-20	1.41 0.30	0.42	1.2
10-21	0.40	0.30	1.3
10-22	0.71 0.30	0.18	1.5

*The calculated size at which a reversal in transport direction occurred.

Figure 3 is a photograph of a trench from the upper foreshore on Oct. 15th illustrating alternating coarse and fine laminations and the bimodality of the beach sediment. The upper coarse layer and the overlying finer laminations were deposited during the previous few days and represent a portion of the Sonu sequence discussed earlier. A major difference between these observations and Sonu's is the more rapid development in this study (a matter of days rather than weeks or months).

Figure 3. Foreshore trench from Oct. 15th, displaying variations in texture and planar laminations.

One of the questions from the the first example is what is the source for the coarse sediment-does it represent onshore transported material or is it an erosional lag? In this second example, we compare profile changes to sediment grain-size changes. The observed sediment sizes are then compared to values predicted to move onshore by the sediment-transport model.

October 12, 1982, was the third day of an extra-tropical storm (northeaster). During the storm, northeast winds reached a maximum sustained speed of 13 m/s at the study site, and maximum significant offshore wave heights reached 2.5 m (Mason and others, this volume). On Oct. 10th, the first day of the storm the foreshore underwent severe erosion with vertical losses greater than 1 m locally. Continued erosion occurred on the 11th but at a much reduced rate. By Oct. 12th offshore significant wave height was 2.5 m and peak period was 15.2 s; both foreshore accretion and erosion were occurring although erosion dominated. Available sediment sizes (Figure 1) varied from fine sand (offshore bar) through medium and coarse sand (inner nearshore and beach) to granules and pebbles (trough).

Several profile and sediment-size changes occurred during the rising tide (Figure 4a). The middle and upper foreshore underwent erosion while the lower foreshore accreted. Coarse sand, granules and pebbles were deposited on the lower foreshore while finer sands were removed from the middle and upper foreshore. The size distributions of the sediments (surficial and subsurface) eroded from the upper foreshore were such that they could not have supplied the volume of coarse material deposited on the lower foreshore. This implies that fine material was removed from the foreshore while, simultaneously, coarse material was derived from an offshore source. During this same period the offshore bar, which was composed of fine sand, was migrating offshore (Figure 4b; Sallenger and Holman,this volume ; Sallenger and others, in press). The most reasonable interpretation is that coarse material was transported onshore to accumulate on the lower foreshore, while finer material was transported offshore, both from the upper foreshore and in the offshore-migrating bar.

The predicted direction of sediment movement for given size classes at selected locations across the nearshore profile are presented in Figure 4b. From the landwardmost sled position, sediment coarser than 0.4 mm (medium sand) is predicted to move landward. This landward transported coarse material probably contributed to the observed coarsening of the lower foreshore. The granules and pebbles deposited on the lower foreshore were considerably coarser than the 0.4 mm predicted reversal size. However, the reversal size indicates only the finest material moving onshore. Elsewhere along the profile the coarsest material predicted to move offshore was medium sand at a point just seaward of the bar crest. All material coarser than very fine sands was calculated to move onshore at the seawardmost sled position and near the deepest part of the trough. The seaward migration of the bar was presumably the result of offshore-transported medium and finer sands.

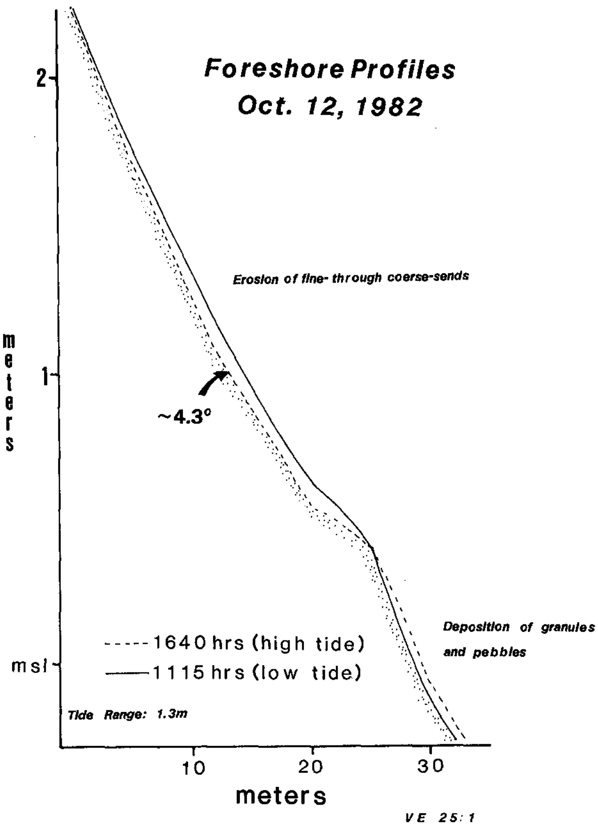

Figure 4a. Foreshore profile and texture changes for Oct. 12th.

Offshore Profiles
Oct. 12, 1982

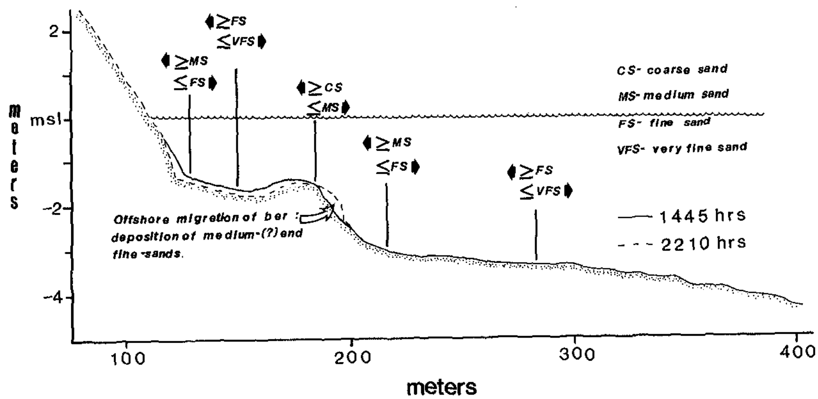

Figure 4b. Offshore profile changes and predicted directions of sediment transport for different grain-sizes at selected sled locations.

CONCLUDING REMARKS

Field evidence from a mixed sandy nearshore supports theoretical predictions that different size classes of sediment can be transported in opposite directions under the influence of the same flow field. Using a sediment transport model, coarse sand was predicted to move onshore as coarse sediment was observed to be accumulating on the foreshore.

The two major parameters responsible for variation in the sediment transport direction are the slope and current velocity. Negative slopes (i.e., a landward slope) introduces some inconsistencies. Onshore transport directions for all sizes studied were predicted for a sled position on the landward sloping bar surface on Oct. 12th. This conflicts with field evidence, based on profile change, of offshore sediment transport for this general location. Theoretically, if the mean offshore currents are strong enough, seaward transport should occur over a landward sloping feature.

The Bagnold efficiency factors, ϵ_s and ϵ_b are another uncertainty. However , we varied these factors within the limits suggested by Bailard (1981) and these changes resulted in reversal size changes of $\pm.25\ \Phi$ --acceptable variations for this study.

Although the results are strictly applicable only to the experimental conditions, they are significant in terms of the transport of any natural sediment or exotic materials such as dredge spoil or beach nourishment fill.

ACKNOWLEDGEMENTS

We would like to thank the entire staff of the FRF for their excellent support in the field. Peter Howd (formerly of OSU) spent many long hours, often under very adverse conditions, measuring sediment levels. David Barnes assisted with the computer programming and Ralph Hunter and Bruce Jaffe made many valuable comments on the manuscript. W. A. Birkemeier (FRF) kindly supplied the sieve data for the offshore samples.

REFERENCES

Bagnold, R. A., 1963: Mechanics of marine sedimentation, in *The Sea, M. N. Hill ed.,* Interscience, v.3:507-528.

Bagnold, R. A., 1966: An approach to the sediment transport problem from general physics. *U.S. Geological Survey Prof. Paper, 422-I.* 37pp.

Bailard, J. A., 1981: An energetics total load sediment transport model for a plane sloping beach. *Jour. Geophys. Research* 86:10938-10954.

Bowen, A.J., 1980: Simple models of nearshore sedimentation; beach profiles and longshore bars. in *The Coastline of Canada, S. B. McCann ed.,* Geological Survey of Canada, Ottawa, 80-10:1-11.

Howd, P. A. and R. A. Holman, In press: Beach foreshore response to long period waves. *19th International Coastal Engineering Conference Proceedings.* This volume.

Mason, C., A. H. Sallenger, R. A. Holman, and W. A. Birkemeier, In press: A comprehensive experiment on storm-related coastal processes. *19th International Coastal Engineering Conference Proceedings.* This Volume.

Murray, S. P., 1967: Control of grain dispersion by particle size and wave state. *Jour. Geology,* 75:612-634.

Sallenger, A. H., P. Howard, C. Fletcher, and P. Howd, 1983: A system for measuring bottom profile, waves and currents in the high- energy nearshore environment. *Marine Geology,* 51:63-76.

Sallenger, A. H., and R. A. Holman, In press: On predicting infragravity energy in the surf zone. *19th International Coastal Engineering Conference Proceedings.* This volume.

Sallenger, A. H., R. A. Holman, and W. A. Birkemeier, In press: Storm-induced response of a nearshore-bar system. *Marine Geology.*

Sonu, C. J., 1972: Bimodal composition and cyclic characteristics of beach sediment in continuously changing profiles. *Jour. Sedimentary Petrology,* 42:852-857.

Zenkovich, V. P., 1967: *Processes of Coastal Development.* Wiley Interscience, N.Y., 738 pp.