CHAPTER 117

SUSPENSION AND TRANSPORTATION OF FLUID MUD BY SOLITARY-LIKE WAVES

John T. Wells, James M. Coleman, and Wm. J. Wiseman, Jr.

Coastal Studies Institute, Louisiana State University

Baton Rouge, Louisiana 70803

ABSTRACT

The suspension and transportation of fluid muds in the nearshore zone by shallow-water, solitary-like waves has been investigated along the coast of Surinam, South America. Accumulations of fluid mud which front the coast at a spacing of 30-60 km affect incoming swell by changing the wave profile from sinusoidal to solitary-like and by preventing wave breaking except for occasional spilling. Simultaneous time-series measurements of wave height and period, fluid-mud density, and tide elevation, along with results of suspended-sediment measurements, indicate that in cases when the bulk density is less than 1.20 g/cm^3 and where water depths are less than 5 m fluid mud is suspended from the bottom in two frequency modes: wave-by-wave suspension (~10 sec) and tide-related suspension (~12.4 hr). Surface-water suspensate concentrations exceed 3.4×10^3 mg/l as up to 0.5 m of fluid mud is periodically removed from the bottom.

High concentrations of suspended fluid mud, together with solitary-like waves from the northeast throughout the year, can lead to extraordinarily high sediment transport volumes. Calculations based on solitary wave theory and on data obtained from this study indicate that 15-65 x 10^6 m^3 of mud can move along shore each year without involving breaking waves, the concept of radiation stress and a nearshore circulation cell, or bed-load transport. These values are 10 to 100 times greater than typical transport rates along sandy coasts.

INTRODUCTION

As a generalization, research on fluid muds prior to the 1970s was restricted almost entirely to the laboratory, and even today field data are scarce. In this study we report results of field measurements conducted along the open, unprotected coast of northeastern South America, where incoming waves are affected by mud shoals composed partly of thixotropic, gel-like fluid muds. Our primary objectives were to examine the interaction between incoming waves and fluid mud and to assess the role of waves in the suspension and transportation of fluid mud.

The lack of field data can be explained partly by the difficulties encountered in obtaining direct measurements of near-bottom processes such as suspension and deposition. Several innovative techniques for studying fine-grained sediment dynamics, including acoustic systems (Kirby and Parker, 1974; Orr and Hess, 1978), a sea-floor flume (Young and Southard, 1978), and nuclear densimeters (Parker et al., 1975), have been utilized in recent years with varying degrees of success. As part of the present study an instrument was developed that could be used as a combination wave gage and sediment-density sensing device. By assuming that variations in mud density must be related to suspension, deposition, and near-bottom transport processes, we have been able to examine the details of fluid-mud dynamics in both intertidal and subaqueous hydrologic settings. Based on actual field measurements and reasonable assumptions, an explanation for transport by waves of suspended fluid mud is presented.

FIELD AREA AND METHODS

During field seasons in 1975 and 1977 data were collected at ten sites off the coast of Surinam, South America, on a section located midway along the 1,600 km of muddy coast that extends from the Amazon River in Brazil to the Orinoco River in Venezuela (Fig. 1). Climatic conditions and coastal processes in the study section are generally representative of those in northeastern South America. The warm tropical climate is controlled by the northeast trade wind system and periods of high and low wind speeds, each several months in duration, alternate throughout the year. During the months of data acquisition, August through October, conditions are typically dry and winds are low to moderate (~10-15 km/hr).

Formed during the Holocene by Amazon-derived muds, the coastline of the Guianas is both interesting and somewhat unique. Linear mud shoals, tens of kilometers long, front the coast at a 30-60-km interval and form a buffer to wave attack, thus controlling the distribution of nearshore wave energy. A spectacular alongshore cycle of erosion and accretion results; in interbank areas, plunging breakers may impinge directly upon stands of mangroves at high tide, whereas in shoal, fluid-mud regions waves are virtually absent at the shoreline and coastal progradation proceeds rapidly. As a result of alongshore mudbank migration, this erosion/accretion system moves to the northwest at an average rate of 1.5 km/yr, suggesting that any given segment of coast has undergone many cycles of erosion and accretion during the last 5,000 yr (Augustinus, 1978).

Simultaneous measurements of wave height and period, fluid mud density variations, suspended-sediment concentration, and tide

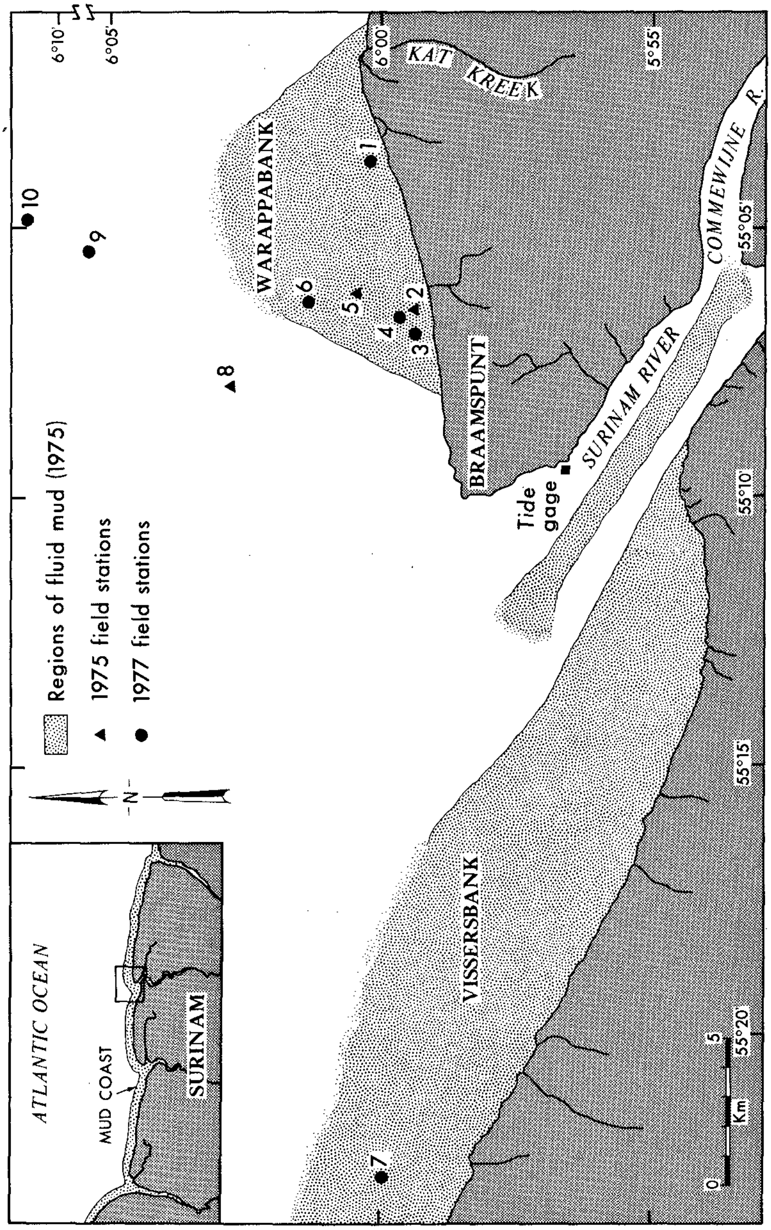

Figure 1. Index map of station locations.

elevation were made at field sites located over Warappabank and Vissersbank, regions where fluid mud up to 1.5 m thick blankets the bottom (stations 1-7, Fig. 1). Wave data were also taken farther offshore where substantial quantities (<0.1 m) of fluid mud are lacking (stations 8-10, Fig. 1). A moderate tide range (~3.2 m at spring tide), combined with a gentle offshore slope, leads to the exposure of a wide expanse of fluid mud at low tide (Fig. 2). Several of our field sites were located in these intertidal regions where water depths never exceeded 2 m (stations 1-3, Fig. 1). At other field sites water depths ranged from 1 to 10 m depending on the location and the stage of the tide.

Fluid mud is defined as a fine-grained sediment-water mixture in which the sediment concentration is greater than 1.0 x 10^4 mg/l (Krone, 1962). Where fluid mud is present the bottom is taken to be the upper surface of the fluid-mud layer, even though survey instruments may penetrate through this layer to more consolidated sediments (Odd and Owen, 1972). Properties of coastal fluid muds in the study area are given in Table 1.

Two Statham Model PA-506 Amplibridge pressure transducers, fastened securely to an adjustable sleeve on pipe that was driven into the bottom, formed the sensing unit of the wave/fluid mud pressure (density) sensing device (Fig. 3). Pressure under a wave, less atmospheric pressure, is given by

$$P = \rho g \ (\eta K_z - z) \qquad (1)$$

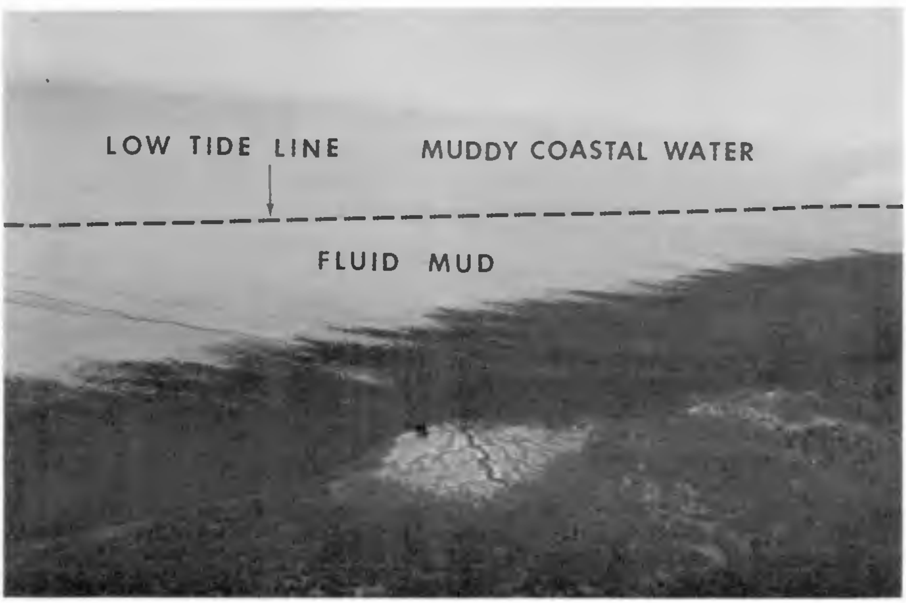

Figure 2. Prograding mudflat photographed at low tide, eastern Surinam coast.

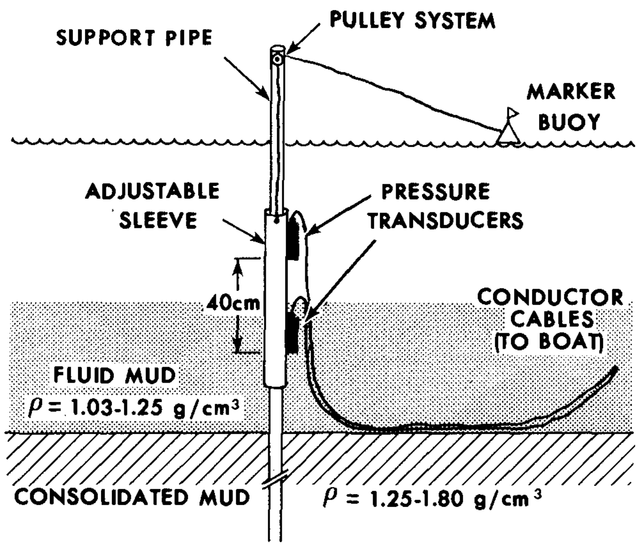

Figure 3. Schematic of field setup for wave/fluid mud pressure-sensing device, showing typical arrangement of pressure transducers relative to fluid-mud layer.

where, in the linearized case,

$$\eta = \frac{H}{2} \cos\left(\frac{2\pi x}{L} - \frac{2\pi t}{T}\right) \tag{2}$$

and the pressure response factor, K_z, is given by

$$K_z = \left(\frac{\cosh\ [2\pi(z+h)/L]}{\cosh\ (2\pi h/L)}\right). \tag{3}$$

In equations (1) - (3), ρ = density of seawater, g = acceleration resulting from gravity, z = distance below still-water level, h = water depth, L = wave length, H = wave height, t = time, T = wave period, and x = horizontal distance. For shallow-water waves such as the tide, $h/L << 0.05$, $K_z \rightarrow 1$, and equation (1) reduces to

$$P = \rho g(\eta - z) = \rho g\ z' \tag{4}$$

where z' can be considered a depth below the time-varying surface. If pressure is measured simultaneously at two depths below the surface, z_A' and z_B', then

$$P_B - P_A = \rho g\ (z_B' - Z_A') \tag{5}$$

Table 1
Properties of Coastal Fluid Muds, Surinam, South America

Bulk density	1.03-1.25 g/cm^3 (1030-1250 kg/m^3)
Water content	64-96%
Voids ratio	4-62
Median particle size	0.5-1.0 micron (disaggregated)
Viscosity	0.02-210 poises

and, provided that $z_B' - z_A'$ is constant with time, any variation in $P_B - P_A$ is directly proportional to a density variation.

For higher frequency gravity waves, say T = 1-15 sec, K_z becomes significant and density can be obtained from equation (5) only if K_z is known at depths z_A' and z_B'. From linear theory, K_z between pressure sensors ranges from 0.01 to 0.07 for wave frequencies encountered in this study. However, observational data indicate that values of K_z are not in perfect agreement with linear theory (Hom-ma et al., 1967; Tubman and Suhayda, 1977), and a correction factor m is usually applied to equation (1). In this study m ranges from 1.0 to 1.05. The determination of density variation from pressure variation is further complicated by the fact that attenuation rate is altered when one transducer is placed in a denser medium than the other, as depicted in Figure 3. Although these problems have been largely overcome by running field tests to determine differential attenuation in clear water and in fluid muds over a range of frequencies, an empirically determined differential density scale has been assigned in cases where $K_z < 1$.

Applying the above concepts in the field, $P_B - P_A$ is nulled out of each transducer electronically by a potentiometer located on the instrument panel (Fig. 4). Once this step is completed, any deviation from the zero null position is directly proportional to a density change. By using 10 or 20 sec time constant filters, high frequency noise is removed from the signal and, if desired, resolution of the signal can be increased up to 0.004 g/cm^3.

In order to obtain useful time-series data, waves were recorded in real time from transducer A simultaneously with the filtered pressure differential between transducers A and B. All data were recorded as analog signals on strip chart recorder. The final step, conversion of differential pressure into absolute density units, required that sediment samples be taken between instrument sensors for initial calibration.

SHALLOW-WATER WAVES

Examination of approximately one hundred and fifty 20-min wave records, taken over all stages of the tide, indicates that waves undergo a severe shoaling transformation when propagating over a fluid-mud bottom. In addition to the rapid height attenua-

Figure 4. Wave/fluid mud pressure-sensing device (recorder not shown).

tion, described qualitatively in previous reports as a major factor in natural sea defenses (Delft Hydraulics Laboratory, 1962; NEDECO, 1968; Augustinus, 1978), waves are deformed from sinusoidal into solitary-like profiles, similar to that which can be observed in gentle swell just prior to breaking. Long, flat troughs separate sharp, isolated crests and, on days when local winds and associated sea chop are low, waves with periods of 15 sec can be recorded.

Information obtained from spectral analysis shows spectral peaks in the frequency range 0.07-0.25 Hz (T = 15 - 4 sec) and H_{rms} of 0.2-1.2 m for waves in water 1-5 m deep. Typical analog wave records and pressure spectra are given in Figure 5 for the consolidated interbank area (station 8), the soft mudbank area (station 5), and for solitary waves given by theory. Note the similarity in profile for waves recorded over a fluid-mud bottom and waves given by solitary wave theory. Wave spectra for solitary-like waves show a wide distribution of variance density with peaks often occurring at harmonic frequencies. Multiple peaks for true solitary waves occur exactly at harmonic frequencies. In interbank areas or farther offshore the spectra display a single well-defined peak in variance density.

In general the boundaries of a mudbank can be delineated simply by the appearance of surface waves (Moni, 1971; Nair, 1976). Height attenuation in the areas between mudbanks is substantially

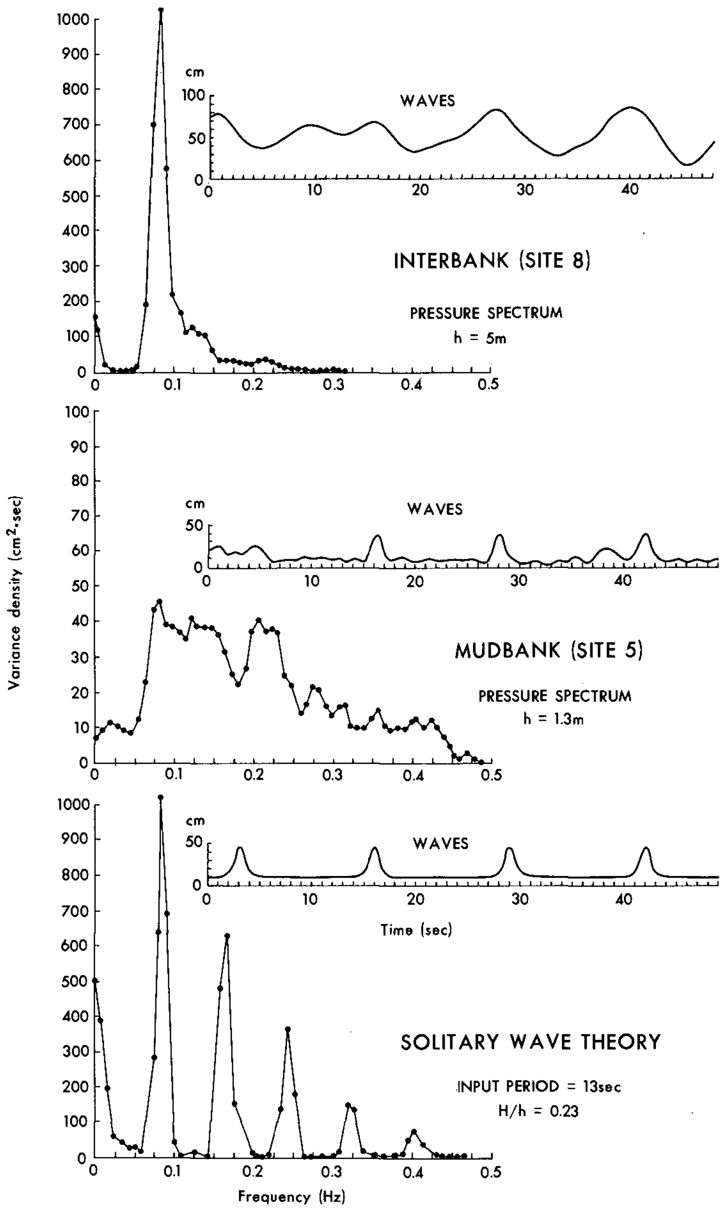

Figure 5. Typical wave records and pressure spectra from interbank area (consolidated bottom, site 8), mudbank area (fluid mud, site 5), and from solitary wave theory.

less and, for a given water depth, wave height may vary by as much as 100% from mudbank to interbank areas. The above generalizations become more complicated in the direction of propagation as waves encounter variations in thickness and density of fluid mud. Analysis currently underway suggests that wave height, period, and form are extremely sensitive to spatial and temporal variations in bottom consistency.

Three features of the solitary-like waves are important with respect to sediment transport. First, they maintain a nearly constant wave height to water depth ratio, $H_{rms}/h = 0.23$, a value that is considerably less than the 0.78 given as the limit of solitary wave theory. In a true solitary wave the volume of water transported is a function of H/h and higher ratios lead to greater transport rates. Second, although spilling breakers have been noted near the shoreline, solitary-like waves over a fluid mud bottom seldom break; rather, they decrease in height until they disappear at the shoreline, indicating that breaking waves and the conventional momentum flux approach to sediment transport problems may not be applicable. Third, waves become noticeably more like true solitary waves in appearance as sediment concentration in water increases. The most solitary-like waves have been observed from mid-tide to mid-tide during the lower half of the tidal cycle.

SEDIMENT SUSPENSION

In the broadest sense, shallow-water waves propagating over a soft muddy bottom maintain a large volume of sediment in suspension. Wells and Coleman (1977) have shown that suspensate concentrations in regions of fluid-mud bottom are orders of magnitude higher than in interbank areas and may attain surface-water values of several thousand milligrams per liter. Some spatial (depth) and temporal (stage of tide) variability also has been observed. Data from that study, combined with data obtained since publication of those results, are given in Table 2. Generally, inshore waters are more turbid than offshore and near-bottom are more turbid than surface waters.

Much of our information concerning suspension processes has been obtained by monitoring density variations in the upper 0.5 m of fluid mud. In general, variations in mud density can result from suspension or deposition, gain or loss of pore waters, and from advection of sediment past instrument sensors. By obtaining measurements over a range of fluid-mud densities (1.03-1.24 g/cm^3) with sensors at several depths relative to the surface of the fluid-mud layer, we have been able to examine details of near-bottom processes in a variety of situations, from which generalizations have been made concerning sediment suspension.

Suspension of sediment by solitary-like waves takes place in two predominant frequency modes: tide-related suspension (~12.4 hr) and wave-by-wave suspension (~10 sec). In mud with a bulk density less than 1.20 g/cm^3 and with water depths less than 5 m, an exchange process between the fluid mud and overlying water operates at the tidal frequency. Data from several field sites (stations 2, 3, and 5) indicate that on a falling tide, near mid-tide level, 10-50 cm of fluid mud is dispersed into water. This

Table 2
Maximum and Minimum Surface Suspended-sediment Concentration, Coast of Surinam

Field Site	Range in Water Depth (m)	Concentration (10^2 mg/l)	
		Maximum	Minimum
1	0.0- 2.0	3.33	0.21
2	0.0- 2.0	2222.85*	26.57
3	0.0- 2.0	52.34	1.09
4	0.5- 2.5	17.75	0.67
5	1.0- 3.0	37.49	0.34
6	1.5- 4.0	11.19	0.82
7	0.5- 2.5	24.51	2.75
8	4.0- 7.0	0.81	0.16
9	4.5- 8.0	0.34	0.14
10	9.0-11.5	No data	taken

*Sampled from surface of fluid mud exposed at low tide.

NOTE: A total of 183 samples was collected. A least squares best fit to all data indicates that concentration varies with height (m) above the bottom, y, as $c = 5.31\ e^{-1.80\ y}$, where c is in killigrams per cubic meter. Coefficient of determination, r^2, is 0.38 ($P < 0.001$).

dispersion is concurrent with the time that waves initially change to the pronounced solitary-like wave profile. Suspended-sediment concentrations increase rapidly and coastal waters become noticeably more turbid. Maximum concentrations of suspended sediment occur at or near low water. On a rising tide concentrations decrease and fluid mud is, presumably, redeposited during the period between mid-tide and high water.

In muds where bulk density exceeds 1.20 g/cm^3, such as interbank areas or the more consolidated eastern edges of mudbanks, less than 1 cm of the bottom is suspended by incoming waves (this value assumes that mass of sediment dispersed into the water reflects the volume of known density removed from the bottom).

Figure 6 shows results of a 3-hr experiment beginning at low tide on an intertidal flat composed of fluid mud with initial density of 1.16 g/cm^3. Five time-series sections, each approximately 20 min, show that bulk density decreased from approximately 1.16 to 1.05 g/cm^3 as water level rose and incoming waves suspended the fluid mud. Figure 7 shows diagrammatically the suspension process. At the termination of this experiment nearly 50 cm of fluid mud had been suspended. The considerable variation in bulk density of fluid mud prior to the first impingement of waves (Fig. 6, sections A and B) was the result of interstitial pressure waves from offshore which, in low density muds, generally preceed

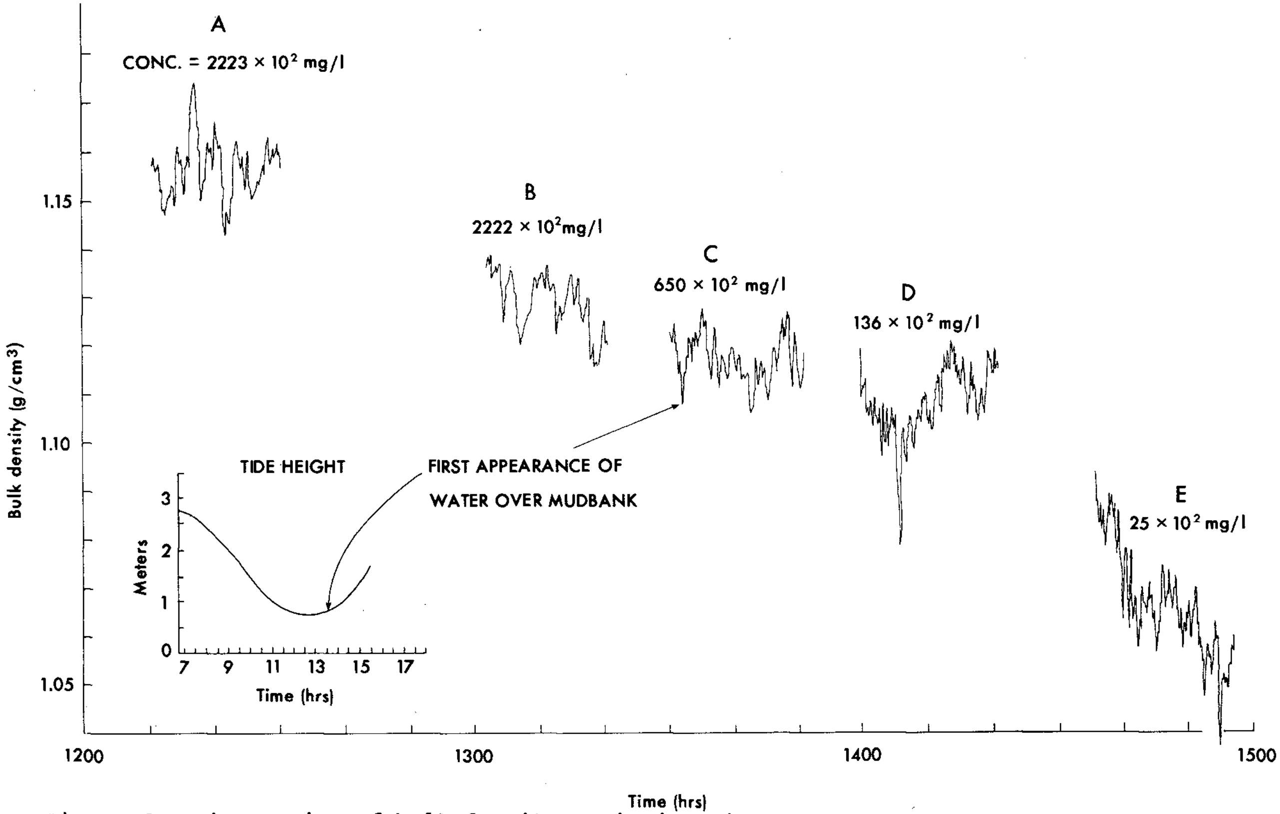

Figure 6. Time series of bulk density variations in upper 0.5 m of fluid mud, beginning at low tide, 8 October 1975. Numbers above each time-series section are surface suspended-sediment concentrations.

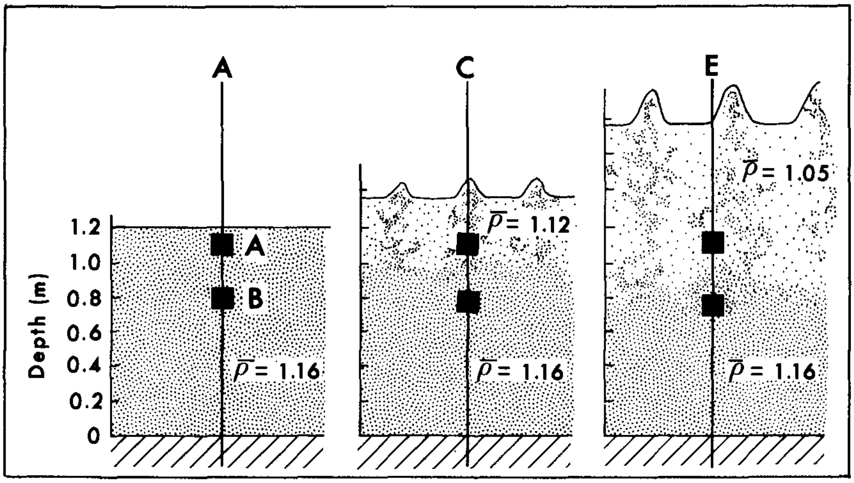

Figure 7. Suspension of Fluid mud by solitary-like waves.

the arrival of surface waves.

The relatively stable wave height to water depth ratio, $H_{rms}/h = 0.23$, may be partly a result of adjustment of the bottom to the amplitude of incoming waves. On days when stronger winds from the northeast produced local waves that were larger than the solitary-like swell waves, suspended-sediment concentrations increased rapidly. Thus, at a given stage of the tide, higher waves suspended more sediment. An example of this process is given in Figure 8. Following a wind shift from southeast to northeast (1200 hr), waves increased in height rapidly and suspended sediment concentration increased by an order of magnitude as fluid mud was suspended at field site #6. The suspension of mud from the bottom was manifested as an overall decrease in bulk density between 1200 and 1400 hr. Field site #9, farther offshore over a relatively consolidated bottom, was unaffected.

Wave-by-wave suspension, often superimposed on the longer term processes described above, is shown in four sections of time series data in Figure 9. As each wave crest passed instrument sensors differential density rose rapidly, then fell gradually; the process repeated when the following wave arrived. The initial explanation of these density variations (Wells, 1977) hypothesized that a cloud of sediment was instantly suspended, followed by rapid settling of this densely flocculated sediment. Based on previous laboratory and field results (Partheniades, 1971; Krone, 1972), it is difficult, to explain such rapid settling, which in this case would require that the center of mass settle at 10 cm/sec. In light of the apparent nonlinear properties of waves, a more plausible explanation may be the advection of this sediment cloud past the sensors. Theoretical bottom particle velocities under solitary waves exceed 100 cm/sec for the range of wave heights observed in this study. The persistence of high-frequency

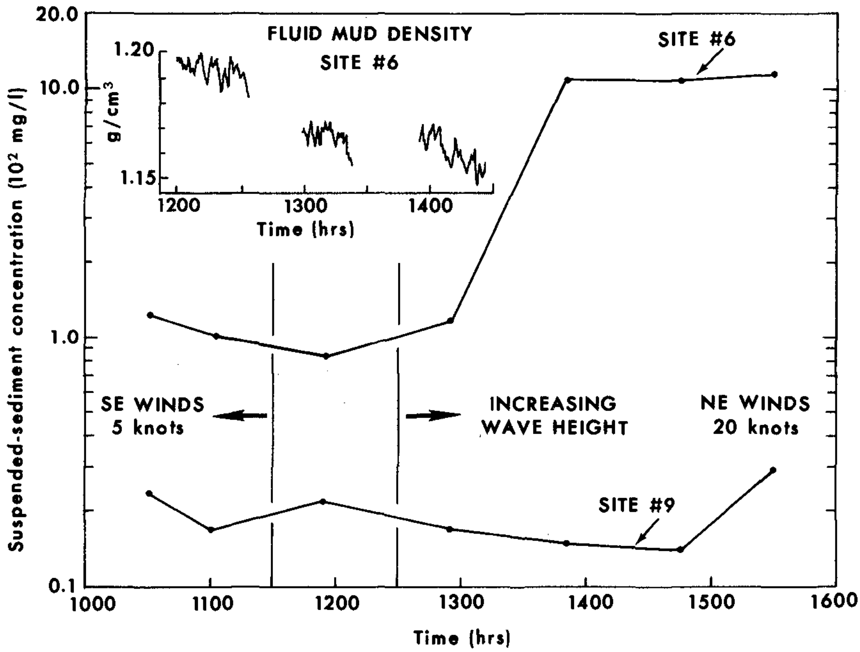

Figure 8. Surface suspended-sediment concentration and fluid-mud density variations, 20 August 1977.

suspension and transport by waves results in temporary or even permanent removal of fluid mud from the bottom. During 3.5 hr of observation (Fig. 9) average density in the upper 0.25 m of fluid mud decreased by 0.04 g/cm^3, an amount that could be achieved only by the removal of 10 cm of fluid mud from the bottom. The possible fate of this suspended fluid mud will be discussed in the next section.

MUD TRANSPORT

Recent estimates of sediment transport along the mud coast of northeastern South America indicate that approximately 20-40% of the total sediment load from the Amazon River makes its way northwestward along the coastlines of French Guiana, Surinam, and Guyana (Eisma and van der Marcel, 1971), resulting in one of the highest littoral transport rates in the world. Approximately 150 x $10^6 m^3/yr$ of "through transport" takes place in the form of suspended sediment, and another 100 x $10^6 m^3/yr$ moves as a result of the propagation of coastal mudbanks to the northwest (summarized from Delft Hydraulics Laboratory, 1962; Gibbs, 1967; Allersma, 1968; NEDECO, 1968; and Eisma and van der Marcel, 1971). Previous investigators have generally attributed these exceedingly high longshore transport rates to suspension of mud by wave orbital

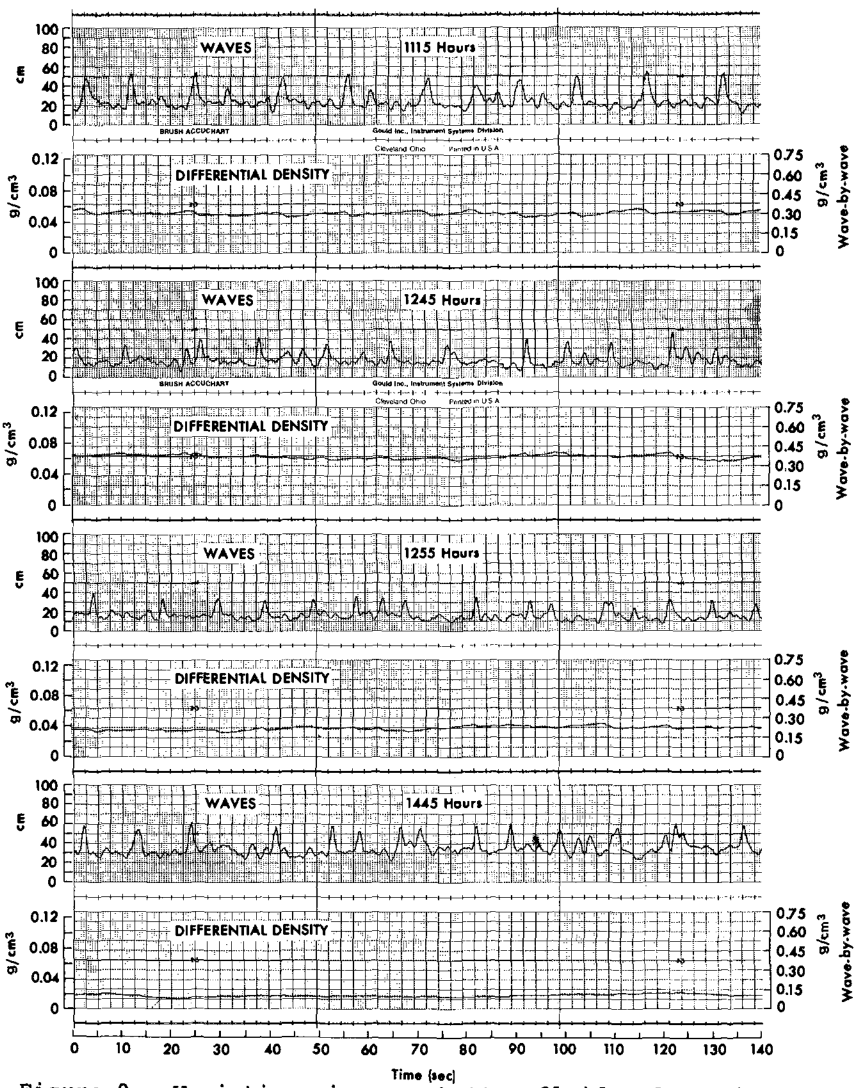

Figure 9. Variations in near-bottom fluid-mud density. Recorded during the passage of waves from HW + 4.5 hr to LW + 2 hr, 26 September 1975. The attenuation of high-frequency signals (less than 100 sec) resulting from a 20-sec time-constant filter requires that a separate scale be used for wave-by-wave variations.

scour, followed by transport to the northwest by the Guiana Current.

The finding in this study that suspensate concentrations are highest in fluid-mud regions where solitary-like waves occur, combined with the fact that 93% of sea and swell arrive at the coastline between N30°E and east (NEDECO, 1968), suggests that a tremendous potential exists for sediment transport by waves acting alone. In theory a solitary wave is a wave of translation whereby water particles move only in the direction of wave travel. Laboratory studies on solitary waves have shown that if wave profile is similar to that given by theory, then particle trajectories are unidirectional and each wave clearly produces a mass transport (Daily and Stephen, 1953). Numerous observations in this and other field studies (for instance, Inman et al., 1963) have provided qualitative verification that particle velocity is greater in the onshore than in the offshore direction for solitary-like waves. In the following paragraphs a simple model for explaining sediment transport, based on results of this study and above-mentioned rationale, is examined.

Consider mass transport of suspended sediment, as applied to surf zone problems, to be given by

$$T_M = \iint_A c\ V\ \sin\alpha\ dA \tag{6}$$

where dA = dxdy, c = suspended-sediment concentration, V = current velocity, and α = angle of wave approach.

Cross-sectional area through which transport takes place (Fig. 10a, b) varies with water elevation, h, and is given by

$$A_i = \int_0^{x_i} h\ dx \tag{7}$$

where horizontal distance, x_i, is determined by h and offhsore slope is given by β. As a simplification, regional variations in water depth that result from fluid-mud suspension and deposition processes (as discussed in the last section) are ignored.

The most justifiable estimate for suspended-sediment concentration is given by the least squares best fit to all suspended-sediment data

$$c = 5.31\ e^{-1.80\ y} \tag{8}$$

where c is concentration in kilograms per cubic meter and applies to any location offshore, y is height above the bottom in meters, and $0 \leq y \leq h = 5$ m.

Assuming pure solitary waves, total volume of a wave per unit crest length above still water level can be obtained as

$$Q = 2 \int_0^{\infty} \eta\ dx \tag{9}$$

where

$$\eta = H \operatorname{sech}^2 \left[\sqrt{\frac{3}{4} \frac{H}{h^3}} \, (x - Ct) \right] \tag{10}$$

and H = wave height, C = wave speed, and t = time. Substituting equation (10) into equation (9) and integrating, Munk (1949) gives

$$Q = 4h^2 \sqrt{\frac{1}{3} \frac{H}{h}} \tag{11}$$

which, averaged over one wave period from the surface to the bottom, gives

$$\bar{V} = \frac{Q}{hT} = \frac{4h(1/3 \; H/h)^{1/2}}{T} \tag{12}$$

as volume transport rate. Investigation of analytical solutions indicates that there is little velocity shear in the vertical, thus a uniform surface to bottom transport rate is reasonable.

Mass transport, averaged over a wave period, now becomes

$$T_M = \sin\alpha \int_X \bar{V} \int_o^{h(x,t)} c \; dy \; dx \; . \tag{13}$$

Average mass transport over a tidal cycle

$$\langle T_M \rangle = \frac{1}{T} \int_o^T \sin \alpha \int_X \bar{V} \int_o^{h(x,t)} c \; dy \; dx \; dt \tag{14}$$

can now be approximated through numerical integration by taking a 2-min time step, an average tide range of 2.5 m, and a water elevation (depth in meters) to be given as

$$h = 3.75 + 1.25 \cos \omega \tag{15}$$

where $\omega = 2\pi \; t/T$.

Finally, if bulk density of the transported mass, including pore space of static grains, is known or assumed, then volume transport is found by dividing by sediment concentration at that density

$$T_V = \frac{T_M}{\rho_c} \tag{16}$$

This allows mass transport values to be converted into units of volume transport that are useful in assessing coastal accretion or erosion.

Volume transport in cubic meters per year is plotted as a function of wave period for angles of wave approach from 6° to 12°, taking $H/h = 0.23$, $\rho_c = 375\ kg/m^3$ ($\rho = 1.25\ g/cm^3$), and $\beta = 0.001$ (Fig. 11). Only transport during one-half of the tidal cycle, that half extending from mid-tide through low water to the following mid-tide, has been considered since this is the time that the most solitary-like waves are observed.

The range in transport spans roughly from 15 to 65 x 10^6 m^3/yr. Higher angles of wave approach lead to higher transport rates, as do shorter wave periods (more pulses of water per unit of time). Values for H/h, ρ_c, and β have been determined from field data and any realistic variations in these parameters will produce small changes in transport values.

Longshore transport rate is most sensitive to horizontal and vertical variations in suspended sediment. Unfortunately, processes controlling the distribution of suspended sediments are more complex and varied than presented here. Thirty-eight percent of the variability in suspended-sediment concentration ($P < 0.001$) can be explained by water depth, leaving 62% to be explained by such factors as local wind-generated waves and density and thickness of the fluid-mud layer. However, inasmuch as most studies of this nature (Galvin, 1973; Komar, 1976) take an average concentration for the entire surf and breaker zone, equation (8) provides an equally good or better estimate.

Values reported in Figure 11 at first appear considerably lower than littoral transport estimates for the coast of northeastern South America, leading one to believe that, even if waves are indeed solitary, only one-quarter or less of the transport can be explained by this mechanism. However, close examination indicates that the total estimated sediment transport rate, cited by previous investigators as 250 x 10^6 m^3/yr, has been determined for a 30-km-wide band extending offshore. If one-sixth of this volume moves alongshore in a band that is only 5 km wide, the width of the hypothetical mudbank in Figure 10a, then the rate becomes 42 x 10^6 m^3/yr and a remarkable similarity can be seen.

Several simplifications that require qualitative evaluation have been introduced into these transport calculations. First, the shoreward component of net drift assumes a return flow to satisfy continuity considerations. If return flow is taken perpendicular to the coastline in the area between mudbanks (Fig. 10a), then longshore transport may be unaffected. This is a logical pattern of onshore/offshore transport since solitary-like waves, which break only by spilling, produce a greater setup over mudbanks than do plunging breakers in areas between mudbanks. In support of this concept, Sonu (1972) has shown that, on the west coast of Florida, wave-induced currents move shoreward over shoals where waves break by spilling and a return flow occurs in troughs where waves break by plunging.

Second, the transport model considers only that transport which occurs in regions of fluid mud, yet assumes that these rates reflect transport in interbank areas as well. This results in an overestimation, even though some transport may take place in interbank areas as a result of an oblique wave approach or by longshore currents produced by breaking waves through the concept

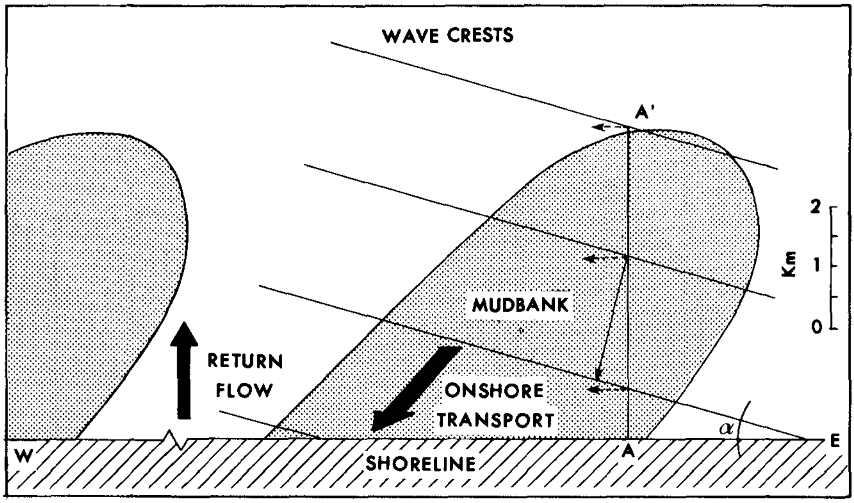

Figure 10a. Plan view of idealized mudbank used in transport calculations. Dashed lines represent longshore component of wave drift.

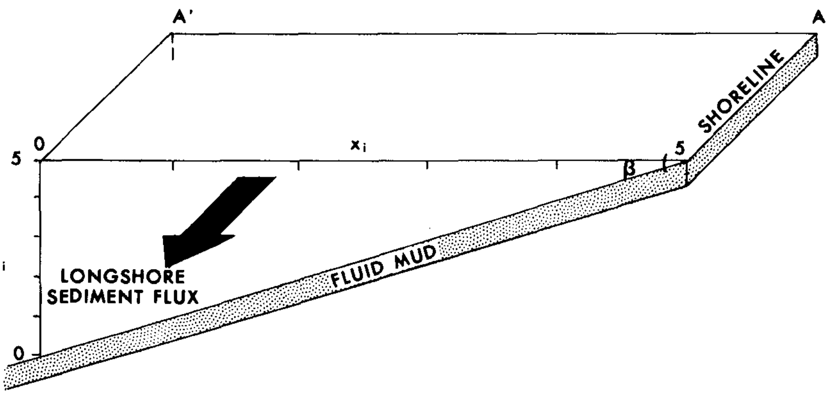

Figure 10b. Cross section along line A-A' (Fig. 10a). Maximum area coincides with high tide when h = 5 m and x = 5 km.

of radiation stress, as normally applied to sandy coasts (Komar, 1976, p. 190). Moreover, all waves over mudbanks are not solitary and probably do not have particle velocities of true solitary waves. Thus, the longshore volume transport rate given in Figure 11 should be considered as an upper bound for that which can be explained by solitary-like waves.

Third, large-scale circulation patterns along this coast are unknown and have been neglected. Such circulation patterns may

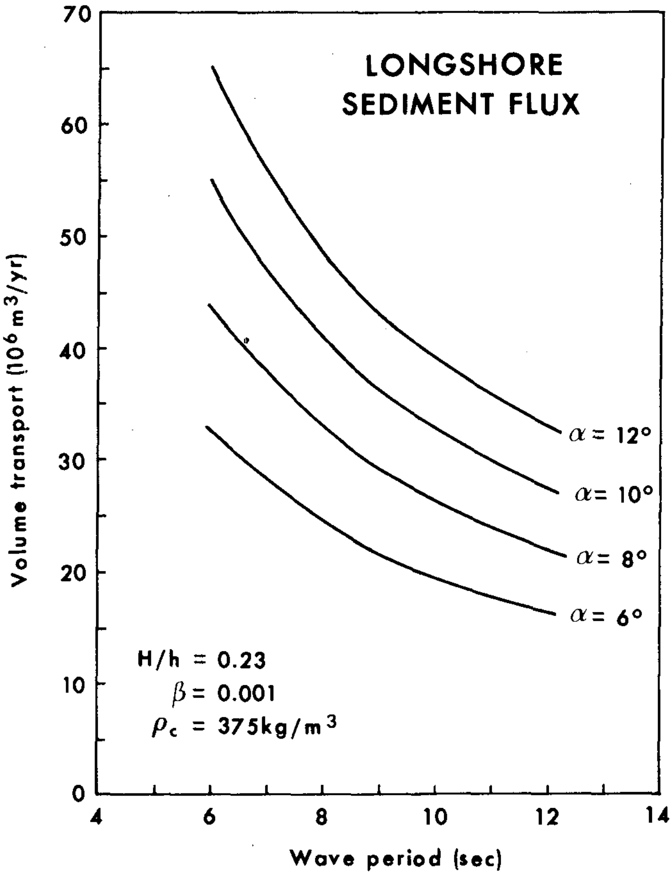

Figure 11. Longshore volume transport as a function of wave period.

provide avenues for moving sediment both onshore and offshore.

Despite the simplifications and unknown processes, the basic conjecture remains that if waves in high suspended-sediment regions have hydromechanical properties of true solitary waves, then sediment transport by waves alone needs to be considered as an explanation for high volume transport rates. The fact that the littoral zone has been taken in this study to extend 5 km offshore, rather than a few meters or a few hundreds of meters, is responsible for longshore sediment transport rates that are orders of magnitude higher than those reported for sandy environments. These estimates, taken across the entire zone in which waves appear to be solitary, may be more realistic than estimates along sandy coasts where only that volume moved by waves in the swash zone is considered.

Finally, we believe the idea presented in this paper, namely that solitary waves can suspend and transport large volumes of fine-grained sediment without utilizing breaking waves, the concept of radiation stress and a nearshore circulation cell or sediment moving as bed load should be vigorously checked along the world's muddy coastlines. A logical next step would be to take field measurements for determination and verification of orbital speeds under solitary-like waves.

ACKNOWLEDGMENTS

This research was performed under a contract between the Geography Programs, Office of Naval Research, Arlington, Virginia 22217, and the Coastal Studies Institute, Louisiana State University, Baton Rouge. Cooperation and field support were provided by Drs. R. A. Cambridge, E. H. Dahlberg, and Th. E. Wong, Government Service for Mining and Geology, Ministry of Development, and Mr. A. M. Sutmuller and his staff, Hydraulic Research Division, Ministry of Public Works and Traffic, Paramaribo, Surinam. Technical assistance in the field was provided by Mr. R. G. Fredericks, and Mrs. A. F. Dunn prepared the illustrations. Drs. S. P. Murray and E. H. Owens reviewed the manuscript and offered helpful suggestions.

REFERENCES

Allersma, E. 1968. Mud on the oceanic shelf off Guyana. Paper contributed to Symposium on Investigations and Resources of the Caribbean Sea and Adjacent Regions, CICAR Conference, Curacao (Delft Hydraulics Laboratory, Delft, The Netherlands, unpublished), 20 pp.

Augustinus, P. G. E. F. 1978. The changing shoreline of Surinam. Unpublished thesis, University of Utrecht, Holland, 232 pp.

Daily, J. W., and S. C. Stephan, Jr. 1953. The solitary wave-its celerity, profile, internal velocities and amplitude attenuation in a horizontal smooth channel. Proc., 3rd Conf. Coastal Engr., Cambridge, Mass., pp. 13-30.

Delft Hydraulics Laboratory, 1962, Demerara coastal investigation. Delft, The Netherlands, 240 pp.

Eisma, D., and H. W. van der Marel. 1971. Marine muds along the Guyana coast and their origin from the Amazon Basin. Contributions in Mineralogy and Petrology 31:321-334.

Galvin, C. J. 1973. A gross longshore transport formula. Proc., 13th Conf. Coastal Engr., Vancouver, B.C., Canada, pp. 953-970.

Gibbs, R. J. 1967. Geochemistry of the Amazon River system. Part I. The factors that control the salinity and the composition and concentration of the suspended solids. Bull. Geol. Soc. Am. 78:1203-1232.

Hom-ma, M., K. Horikawa, and S. Komori. 1967. Response characteristics of underwater wave gage. Proc., 10th Conf. Coastal Engr., Tokyo, Japan, pp. 99-114.

Inman, D. L., W. R. Gayman, and D. C. Cox. 1963. Littoral sedimentary processes on Kauai, a subtropical high island. Pacific Science XVII:106-129.

Kirby, R., and W. R. Parker. 1974. Seabed density measurements related to echosounder records. Dock and Harbour Authority 54:423-424.

Komar, P. D. 1976. Beach processes and sedimentation. Englewood Cliffs, New Jersey (Prentice-Hall), 429 pp.

Krone, R. B. 1962. Flume studies of the transport of sediment in estuarial shoaling processes. University of California Hydraulic Engr. Lab. and Sanitary Research Lab., Berkeley, 110 pp.

Krone, R. B. 1972. A field study of flocculation as a factor in estuarial shoaling processes. Committee on Tidal Hydraulics, Corps of Engr., Vicksburg, Miss., Tech. Rept. 16, 62 pp.

Moni,N. S. 1971. Study of mudbanks along the southwest coast of India. Proc., 12th Conf. Coastal Engr., Washington, D.C., 2:739-750.

Munk,W. H. 1949. The solitary wave theory and its applications to surf problems. Ann. N. Y. Acad. Sci. 54:376-424.

Nair,R. R. 1976. Unique mud banks, Kerala, Southwest India. Bull. Am. Assoc. Petrol. Geologists 60:616-621.

NEDECO. 1968. Surinam transportation study. Netherlands Engr. Consultants, The Hague, 293 pp.

Odd, N. V. M., and M. W. Owen. 1972. A two-layer model of mud transport in the Thames estuary. Proc. Inst. Civ. Engr., Supplement Paper #7517S, pp. 175-205.

Orr, M. H., and F. R. Hess. 1978. Remote acoustic monitoring of natural suspensate distributions, active suspensate resuspension, and slope/shelf water intrusions. J. Geophys. Res. 83:4062-4068.

Parker, W. R., G. C. Sills, and R. E. A. Parke. 1975. In-situ nuclear density measurements in dredging practice and control. 1st Internat. Symp. on Dredging Tech., pp. B3-25 - B3-42.

Partheniades, E. 1971. Erosion and deposition of cohesive materials. In (H. W. Shen, ed.) River mechanics. Boulder (Colorado State Univ. Press), pp. 25-1 - 25-91.

Sonu,C. J. 1972. Field observation of nearshore circulation and meandering currents. J. Geophys Res. 77:3232-3247.

Tubman, M. W., and J. N. Suhayda. 1977. Wave action and bottom movements in fine sediments. Proc., 15th Conf. Coastal Engr., Honolulu, 2:1168-1183.

Wells, J. T. 1977. Shallow-water waves and fluid-mud dynamics, coast of Surinam, South America. Ph.D. dissertation, Coastal Studies Inst., Louisiana State Univ., Baton Rouge, 99 pp.

Wells, J. T., and J. M. Coleman. 1977. Nearshore suspended sediment variations, central Surinam coast. Marine Geology 24:M47-M54.

Young, R. N., and J. B. Southard. 1978. Erosion of fine-grained marine sediments: sea-floor and laboratory experiments. Bull. Geol. Soc. Am. 89:663-672.