LONGSHORE TRANSPORT OF MUD BY WAVES: NORTHEASTERN COAST OF SOUTH AMERICA

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ABSTRACT

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Time series measurements of waves and wave/mud interactions along the Surinam coast indicate that waves may play a greater role than previously thought in the suspension and transport of fine-grained sediment on the northeastern coast of South America. Accumulations of fluid mud or slingmud that occur on western flanks of migrating mudbanks affect incoming swell by changing their form from sinusoidal to solitary-like and by preventing wave breaking except for occasional spilling. As solitary-like waves propagate over the soft-mud bottom, fluid mud is suspended, resulting in surface suspensate concentrations that exceed 3.10^3 mg/l.

The presence of solitary waves, high suspended-sediment concentrations, and a relatively uniform angle of wave approach throughout the year may lead to extraordinarily high sediment transport rates. If waves are assumed to have a net drift as given by solitary wave theory, then, in taking angle of wave approach and actual measured concentration of sediment in suspension, enough sediment can be transported by waves alone to explain the propagation of mudbanks by fluidmud transport. On the basis of reasonable wave and sediment conditions, it is estimated that up to 70.10^6 m^3 of mud can be transported alongshore each year.

INTRODUCTION

Recent estimates of sediment transport along the muddy coast of northeastern South America indicate that approximately 20-40 percent of the total sediment load from the Amazon River makes its way northwestward along the coastlines of French Guiana, Surinam, and Guyana (EISMA & VAN DER MAREL, 1971), resulting in one of the highest littoral transport rates in the world. Approximately 150×10^6 m^3/year of 'through transport' takes place in the form of suspended sediment, and another 100×10^6 m^3/year moves as a result of the northwestward propagation of coastal mudbanks (summarized from DELFT HYDRAULICS LABORATORY, 1962; GIBBS, 1967; ALLERSMA, 1971; NEDECO, 1968; EISMA & VAN DER MAREL, 1971). Previous investigators have generally attributed these exceedingly high longshore transport rates to suspension of mud by wave orbital scour, then transport by the northwesterly flowing Guiana Current. However, recent field experiments provide convincing evidence that waves alone may be the mechanism largely responsible for suspending and transporting large volumes of sediment, even in the absence of a coastal current or a residual oceanic current. The purpose of this paper is to present results of direct measurements of waves and to assess the role of waves in transporting fine-grained sediment along this part of the South American coast.

The 1600 km of coastline between the Amazon and Orinoco Rivers is both interesting and unique. The longest uninterrupted muddy coast in the world, it was formed during the Holocene by sediment derived from the Amazon River. Large migrating mudbanks, parts of which are composed of thixotropic gel referred to as fluid mud or slingmud, front the coast every 30-60 km and form a buffer to wave attack. Thus the distribution of nearshore wave energy is controlled primarily by these mudbanks, and a spectacular cycle of erosion and accretion results as mudbanks propagate to the northwest.

ZONNEVELD (1954) has explained the transport resulting from westward migration of mudbanks as the erosion of their eastern edge by waves, then the transport of the eroded clay from the eastern to the western side, where it accumulates as soft, fluid mud. According to VANN (1959), once in suspension the mud may be transported westward by longshore currents set up by breaking waves. Extensive field studies by DELFT HYDRAULICS LABORATORY (1962) and NEDECO (1968) reported that, although high waves entrain sediment into the water,

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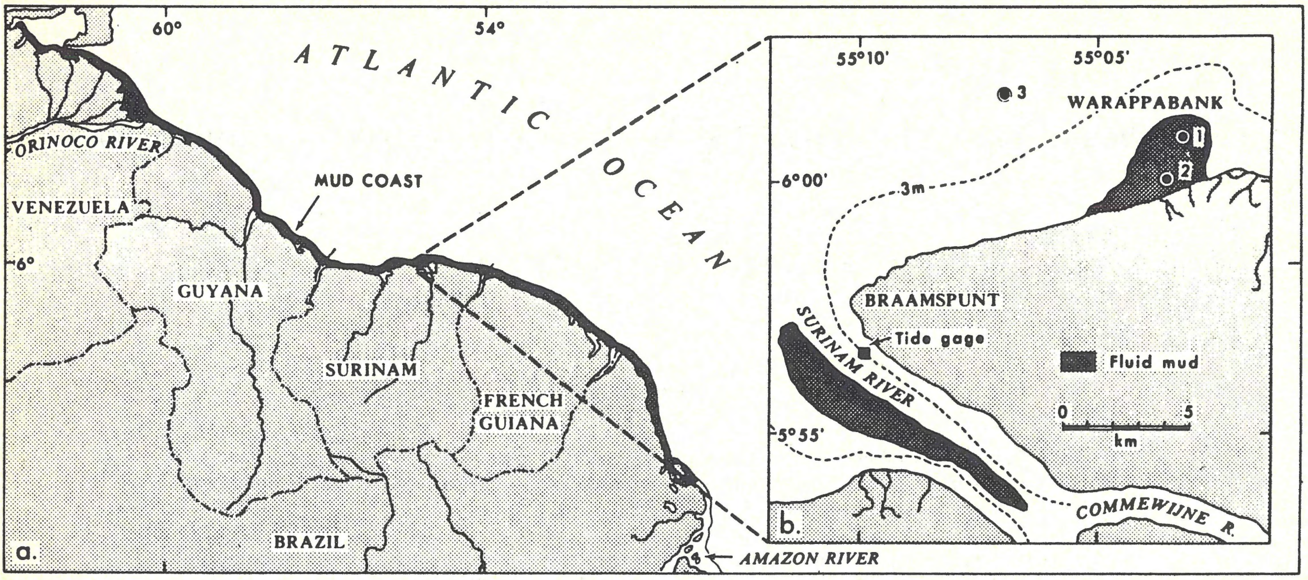

Fig. 1
Muddy coast of northeastern South America (a) and region of field measurements, Surinam coast (b). The 3-m depth contour is referenced to mean low water.

large-scale transport requires the aid of a current. In the above-named studies the role of waves in suspending and transporting sediment was reported almost exclusively from visual estimates. Thus the need for quantitative wave data exists, as was pointed out in 1971 by ALLERSMA:
"It is felt that one or more series of observations with instruments, combined with a thorough analysis of the records, might reveal some facts that cannot be obtained from visual observations".

A series of low-altitude aerial flights over the Surinam coast in 1975 stimulated the authors to obtain detailed measurements of waves and wave/mud interactions in order to further examine the possibility of sediment transport by waves. In the following paragraphs, results of field studies conducted along the central Surinam coast are presented and an explanation for sediment transport by waves is offered.

FIELD AREA AND METHODS

The country of Surinam, situated midway between the Amazon and Orinoco Rivers (Fig. 1a), has coastal conditions typical of the northeastern coast of South America. The warm tropical climate is controlled by the northeast trade wind system. Although severe storms and hurricanes do not occur, alternating wet, windy and dry calm periods are present throughout the year. September and October, the months during which field data were obtained, are typically dry, and relatively calm sea conditions prevail.

Time series measurements of waves and fluid-mud density variations were taken simultaneously with tide elevation and suspended sediment data at field sites shown in figure 1b. The field sites represent three hydrologic settings common to this muddy coastline: subaqueous mudbank (site 1); intertidal mudbank (site 2); and area between mudbanks (site 3). Depending on stage of the tide (range 3.2 m at spring tide), water depths ranged during data collection from 1 to 3 m on the subaqueous mudbank, 0 to 2 m on the intertidal mudbank, and 5 to 8 m between mudbanks. Wave and fluid-mud density data were taken with a prototype wave/fluid-mud pressure-sensing device designed for utilization in muddy environments. Tide elevation was recorded on a pressure-transducer water-level gage located in the Surinam River entrance. Suspended sediment concentration was determined from water samples taken at 0.5-1.0-hr intervals, and several particle-size determinations were made from bottom grab samples.

RESULTS

Wave characteristics

Examination of sixty-five 20-min wave records, taken over 5 sampling days, indicates that waves in the nearshore, with respect to wave form, are of two types: sinusoidal and solitary-like. In water 5-8 m deep between mudbanks, waves are generally sinusoidal, 0.5 m in height, and 12-15 sec in period. Wave length (L) and water depth (h) in the ratio h/L indicate that these are intermediate (transitional) water waves (COASTAL ENGINEERING RESEARCH CENTER, 1973).

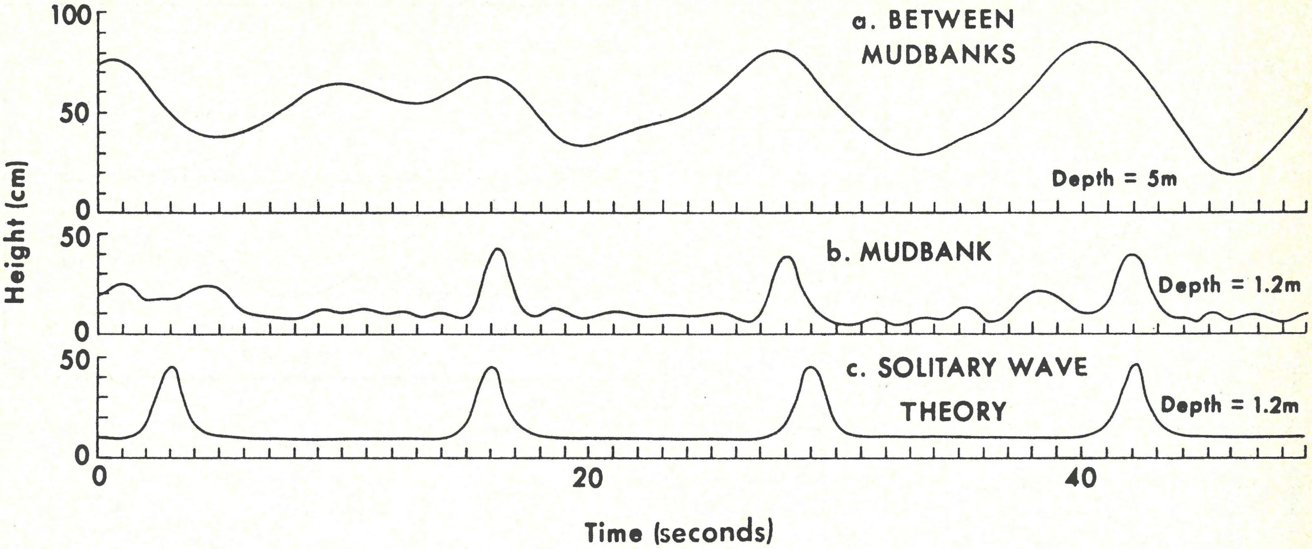

Fig. 2
Sinusoidal wave form in an area between mudbanks (a), solitary-like wave form over an subaqueous mudbank (b), and wave form as given by the solitary-wave theory (c).

A remarkable change in wave shape takes place when waves first propagate as shallow-water waves ($h/L < 0.05$) over the soft, fluid-mud bottom. Wave records taken over mudbanks show that wave form closely approximates that for theoretical solitary waves. Isolated crests are separated by flat troughs lying at still-water level. Wave period is 12-16 sec and, in water 1-3 m deep, wave height is 0.1-0.5 m. Crests are steep and symmetrical and display lateral continuity, estimated from aerial reconnaissance to be more than 1 km. Examples of the two types of wave forms are given in figure 2a and b; the theoretical solitary wave form is given in figure 2c.

At low tide, when banks of fluid mud are exposed, waves may spill directly onto the fluid mud itself. During a rising tide there is no return flow associated with incoming waves; each wave simply advances farther toward shore and the water motion becomes borelike. Field observations revealed that, except during low tide, when waves spill onto mudbanks, little wave breaking takes place. Rather, wave height is continuously attenuated as waves travel with a solitary-like form for several kilometers or more. Measurements at field sites 1 and 2 indicate that as wave height (H) decreases with decreasing water depth, a nearly constant ratio of $H/h = 0.23$ is maintained.

Suspended sediment

Sediment in suspension is composed of aggregates of predominantly clay-sized particles. Typical particle-size distributions of Surinam muds from several locations along the coast indicate that median particle size in dispersed form is 1 μm or less (Fig. 3). Further details of size distributions, as well as mineralogical analyses, have been reported previously (e.g., DELFT HYDRAULICS LABORATORY, 1962) and will not be repeated here.

Extremely high concentrations of suspended sediment occur over banks of fluid mud, whereas substantially lower concentrations occur farther offshore or in areas between mudbanks. Results of suspended-sediment sampling are given in summary form in Table I. In addition to the overall high concentrations in regions of fluid mud, large variations in concentration occur in these areas. Figure 4 shows a typical example of suspended-sediment concentration variation as related to stage of the tide. The major features of this figure are a rapid increase at mid-tide, peak at low water, and then a steady decrease up to the following high tide; a suspended-sediment concentration change of more than 2 orders of magnitude takes place during a tidal cycle. In contrast, no trend related to tide elevation could be observed in the area between mudbanks (site 3), and concentrations remained 1-2 orders of magnitude lower than those cited above.

Wave/Mud interactions

The high concentrations of suspended sediment over the mudbank, particularly at low water, are a result of fluid-mud suspension by solitary-like waves. Nearshore waters are noticeably more turbid on days when waves are higher and, because of this, the thickness of fluid mud overlying the consolidated mud bottom depends partly on wave height. In

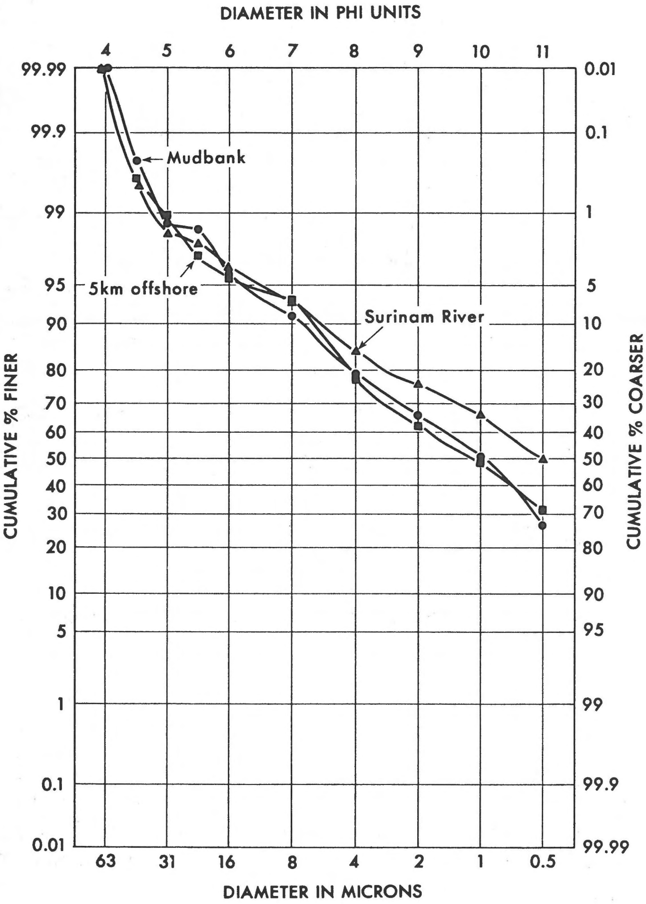

Fig. 3
Characteristic particle-size distributions, central Surinam coast.

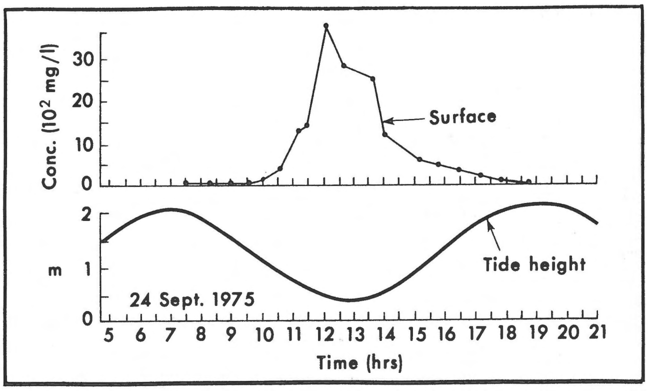

Fig. 4
Suspended-sediment variations, subaqueous mudbank (site 1).

shallow water over mudbanks the effect of fluid-mud suspension can be detected as a near-bottom decrease in fluid-mud density. Figure 5 shows a time series record of surface-water waves and near-bottom fluid-mud density taken from the upper 40 cm of a fluid-mud deposit. During the 2 min of data shown in this figure, average fluid-mud density decreased from ~ 1.13 to 1.09 g/cm^3 as several centimeters of soft mud was suspended. This section of time series was part of a 4-hr experiment, conducted during falling tide, in which approximately 20 cm of fluid mud was suspended. Also of interest in these data are high-frequency density perturbations, perhaps the result of a wave-like rise and fall of fluid mud past the sensing instrument.

Table I
Maximum and Minimum Suspended-Sediment Concentration at Three Field Sites, Central Surinam Coast

Hydrologic Setting	Sampling Depth	Concentration Maximum (10^2 mg/l)	Concentration Minimum (10^2 mg/l)	Range in Water Depth (m)
Subaqueous Mudbank (site 1)	Surface	37.49	0.34	1-3
Intertidal Mudbank (site 2)	Surface	2222.85*	26.57	0-2
Between Mudbanks (site 3)	Surface	0.27	0.14	
	Mid-depth	0.82	0.16	5-8
	Bottom	1.22	0.92	

*'Suspensions' with concentrations greater than 100×10^2 mg/l are generally referred to as fluid mud (see Krone, 1962). Maximum values at site 2 correspond to samples from mudbank surface exposed at low tide.

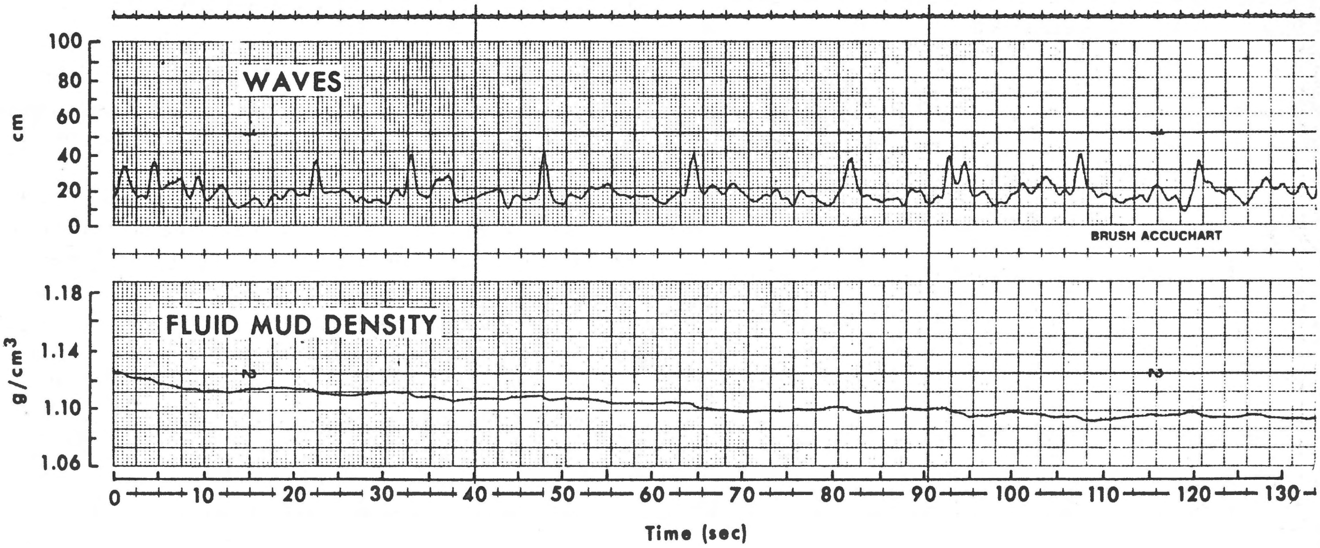

Fig. 5
Variations in near-bottom fluid-mud density, subaqueous mudbank (site 1).

LONGSHORE TRANSPORT

The finding in this study that solitary-like waves are present in regions where suspended-sediment concentrations are highest, namely over banks of fluid mud, is important with respect to longshore sediment transport. A true solitary wave is a wave of translation; unlike oscillatory waves, there is no reversing flow, and water particles move only in the direction of wave travel. As a result, sediment particles may be transported in the direction of wave travel by wave-induced currents.

Examination of data presented in NEDECO (1968) indicates that 93% of sea and swell arrive at the coastline from North 30° East to East. Furthermore, monthly frequency curves show that waves arrive from a northeast quadrant every month, thereby producing a year-round drift component to the northwest. The combined effect of northwesterly drift from solitary-like waves and suspended-sediment concentrations that exceed 3×10^3 mg/l every tidal cycle produces a potential for extraordinarily high volume transport rates. In the following paragraphs, a simple model for explaining sediment transport, based on the above results and rationale, is examined.

Consider mass transport to be given by

$$T_M = cAv \qquad (1)$$

where A is the cross-sectional area and c and v are the time- and depth-averaged suspended-sediment concentration and current velocity, respectively. If bulk density of the transported mass after deposition is known or assumed, then volume transport is found by dividing by sediment concentration at that density

$$T_v = \frac{T_M}{P_c}\,. \qquad (2)$$

Next, consider transport to be through a cross-sectional area determined from the width of a mudbank and the average water depth over that mudbank. Since the longshore component of transport depends on angle of wave approach, eq. 2 becomes

$$T_v = \frac{cAv}{P_c} \sin \alpha. \qquad (3)$$

A diagrammatic illustration is given in figure 6.

Assuming that solitary wave theory provides a reasonable description of waves over mudbanks, the total volume per unit crest length above still-water level can be obtained as

$$Q = \int_{-\infty}^{\infty} \eta\, dx = 2 \int_{0}^{\infty} \eta\, dx \qquad (4)$$

where

$$\eta = H\, \mathrm{sech}^2 \left[\sqrt{\frac{3}{4}\frac{H}{h^3}}\,(x - Ct) \right] \qquad (5)$$

describes a solitary wave profile for H = wave height, h = water depth, x = horizontal distance, C = wave speed, and t = time. Substituting eq. 5 into eq. 4 and integrating gives, to a good approximation (see MUNK, 1949),

$$Q = 4h^2 \sqrt{\frac{1}{3}\frac{H}{h}} \qquad (6)$$

Since a volume transport equal to Q takes place during one wave period (T) the mean transport per unit time equals Q/T and volume transport velocity, averaged from the surface to

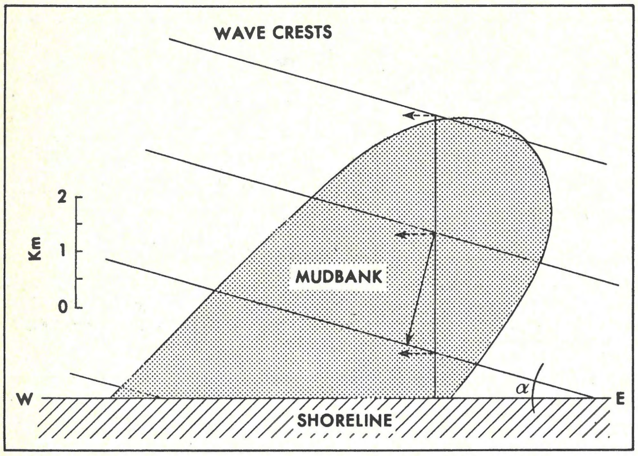

Fig. 6
Idealized mudbank, coast of Surinam. Dashed lines represent longshore components of wave drift.

the bottom, yields

$$\bar{V} = \frac{Q}{hT} = \frac{4h(1/3\ H/h)^{1/2}}{T}. \qquad (7)$$

Equation 7 has units of LT^{-1} since Q is taken to be volume per unit length of wave crest and can be substituted into eq. 3 for v.

By taking measured values of suspended-sediment concentration and wave height and period over mudbanks, volume transport rates up to 70×10^6 m^3/yr can be obtained over a 5-km-wide mudbank (Fig. 7). Volume transport curves in figure 7 for $H/h = 0.23$, the value observed in the field, and $H/h = 0.78$, the value given by solitary wave theory, show the effect of increasing wave height on sediment transport. A change of approximately 2 orders of magnitude takes place as wave height increases from 10 to 100 cm, maintaining a constant H/h ratio. The lower transport rates for higher H/h ratios (0.78 versus 0.23) are due to the fact that, for given wave height, water depth is less for $H/h = 0.78$ than for $H/h = 0.23$, and volume of water in a solitary wave is related to the square of depth (eq. 6).

Volume transport will increase linearly with increases in suspended-sediment concentration, cross-sectional area, and portion of the tidal cycle over which waves are considered to be solitary (3 hr/tidal cycle for values obtained in Fig. 7). Higher angles of wave approach will also lead to higher transport rates, although actual variations are small. The total estimated sediment transport rate, cited by previous investigators as 250×10^6 m^3/year, was determined for a 30-km-wide band extending alongshore. 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 6, then the rate would be 42×10^6 m^3/year, less than that which can be explained by the longshore component of wave-associated currents.

Several simplifications that require qualitative evaluation have been introduced into these transport calculations. First, the longshore component of net drift has been determined under the condition that no coastal boundary exists. This is clearly unreasonable, and the shore-directed net drift component requires a compensating return flow to satisfy continuity considerations. However, if a uniform return flow is taken perpendicular to the coastline, then longshore transport is unaffected. Second, the transport model considers only that transport which occurs in regions of fluid mud, and only that sediment which is in suspension. These may underestimate sediment transport rates, since transport may take place between mudbanks resulting from an oblique wave approach or longshore currents produced by breaking waves through the concept of radiation stress and a nearshore circulation cell, as now generally applied to sandy coasts (KOMAR, 1976, p. 190). Furthermore, fluid mud may move en masse, and extremely high concentrations, say 2-20 $\times 10^3$ mg/l, may travel in a flow near bottom, as has been found in estuarine fluid muds (INGLIS & ALLEN, 1957). Third, large-scale coastal circulation patterns along this coast are unknown and have been neglected. Such circulation patterns may 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. Perhaps, though, these estimates, taken across the entire zone in which waves appear to be solitary, are more realistic than estimates along sandy coasts where only that volume moving by waves in the swash zone is considered.

CONCLUSIONS

(1) If waves are assumed to have a net drift as given by solitary wave theory, then enough sediment can be transported by waves alone to explain the propagation of mudbanks by transport of suspended fluid mud.
(2) Longshore sediment transport may be higher in the dynamic nearshore region, where suspended sediment concentrations are high and solitary-like waves occur, than in lower concentration areas, where a residual current is present.
(3) In view of the above conclusion, an appropriate explanation for longshore sediment transport along the northeastern coast of South America may require the combination of wave-induced currents in the nearshore region over mudbanks and a residual current farther offshore.
(4) Although data were collected on one mudbank only, on the basis of extensive aerial and ground reconnaissance it is concluded that solitary waves, high suspended-sediment con-

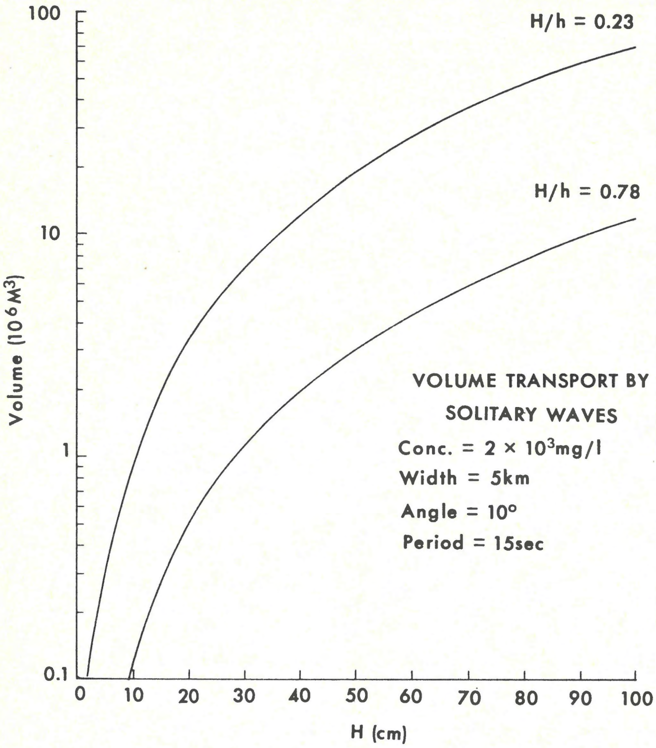

Fig. 7
Volume transport of sediment by solitary waves for H/h = 0.23 (observed) and H/h = 0.78 (theory).

centrations, and similar wave/mud interactions occur along other parts of the Surinam coast and perhaps as far northwest as the Orinoco River and as far southeast as the Amazon River.

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