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ESTUARINE FLUID MUD: ITS BEHAVIOR AND ACCUMULATION

Final Report

by Maynard Nichols, Richard Faas and Galen Thompson

April 1979

For: U.S. Army Research Office
P.O. Box 12221
Research Triangle Park
North Carolina 27709

Under Grant: DAAG29-76-G-0086

To: Virginia Institute of Marine Science
Gloucester Point, Virginia 23062

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A study of fluid mud in Virginia estuaries was conducted to determine how the mud accumulates in a dynamic tidal flow regime. The mud occurs as lenses and blanket deposits in zones of fast sedimentation, i.e. on channel floors and in the turbidity maximum zone. Viscosity measurements indicate resuspension potential of the mud is greater in the turbidity maximum than elsewhere.

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CON'T → Time-series measurements over a tidal cycle at 6 cm above the bed show that stress increased linearly with acceleration of mean current but lagged maximum current velocity during deceleration of tidal currents. Fluid mud-flow interactions are primarily responsible for accumulation of the mud.

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FORWARD

This report summarizes results of a study concerning the behavior and accumulation of fluid mud in estuaries. It is prepared to conform with ARO 70-31 and instruction 18 of 31 July 1975 and contains the requested information: (1) a statement of the problem, (2) a summary of important results, (3) a list of publications, (4) a list of participating scientific personnel.

1. Introduction

Masses of soft mud are observed on the floor of many estuaries. These dense suspensions of sediment, variously called "fluff", sludge, "slingmud" or "creme de vase" occur as transient layers, ephemeral pools and lenses 0.01 to 10.0 meters thick. The term "fluid mud" is a descriptor to describe mud of high water content with densities in the range 1.005 to 1.30 g/cc corresponding to concentrations of 10 to 480 g/l.

2. Statement of the Problem

Whereas much sediment in estuaries is deposited directly by settling out from suspension in the water column, a substantial amount of sediment may undergo repeated resuspension and settling. This fraction then accumulates as dense suspensions of fluid mud despite fast currents that exceed speeds normally required to erode the mud. Because fluid mud forms in dynamic flow regimes, it is logical to ask: What processes are responsible for its accumulation? In turn, how does the mud maintain its integrity and resist shear under stress of tidal currents and intense turbulence? These questions were approached by examining (1) the fluid stress on the mud surface, (2) the cohesive properties of the mud, and (3) the dynamic interaction between the mud and water.

According to a model developed by McCave (1970), deposition of suspended sediment is accomplished by *trapping in a viscous sublayer of the boundary layer*. Trapping occurs below a limiting shear stress for deposition. Consequently, deposition does not depend on the critical flow velocity but is controlled by the balance between input to, and ejection from, the sublayer. Deposition is essentially a function of the settling velocity. The model is valid at low shear values ($U_* < 1.2$ cm/sec) and neglects the influence of organisms and bed roughness. The rate of deposition is given by:

$$dm/dt = C_s W$$

where C_s is the concentration of suspended sediment of settling velocity W, just above an assumed plane which is taken as the edge of the viscous sublayer.

Another model postulates periodic settling at each slack tide. Krone (1962) deduced a linear relation between rate of deposition and shear stress given by:

$$R = C_s W \, (1 - \tau_o/\tau_1)$$

where τ_1 is the limiting shear stress for deposition and τ_o the bottom shear stress. The occurrence of fluid mud is an indication of the long-term balance between the factors C_s, W and p, i.e. the probability of deposition which depends on the time for which $\tau_o < \tau_1$.

Once deposited, fluid mud may transform into semi-consolidated mud masses; alternately, it may be eroded. Krone (1962) showed that resistance to erosion of a bed is controlled by the strength of sediment aggregates and inter-particle bonding. For erosion to occur, the aggregates have to be stripped off the bed. The erodibility varies according to composition of the sediment, pore water salinity, water content, bulk density, sediment viscosity and related properties. Additionally, the rate of erosion is affected by the applied shear stress over a critical value. A bed may fail if the applied stress exceeds the shear strength of the deposit.

Only limited attention has been given to investigating fluid mud behavior and its accumulation in estuaries. Instrumentation and techniques for performing field observations are inadequate.

Research effort of this study consisted of:

1. Evaluation of instrument performance through laboratory and field tests.

2. Field observations of fluid mud properties, thickness and distribution in the James and Rappahannock Estuary, Virginia, and in Upper Chesapeake Bay.

3. Tidal current time-series measurements in the Rappahannock Estuary to derive bed shear stress and Reynolds stress.

3. Field Instrumentation

A new instrumented tripod, the "Sediment-Water Interface Probe" was constructed to investigate the vertical distribution of mud density and to obtain *in situ* time-series measurements of current speed and sediment concentrations close to the mud-water interface. Configuration of the unit is shown in Figure 1 and the sensors deployed are listed in Table 1. Sensor signals were recorded on shipboard readouts, analogue recorders, a Fluke model 2200 B data logger and Kennedy magnetic tape recorder. Additionally, fluid mud layers were traced acoustically with a dual-frequency Raytheon fathometer of 22.5 and 200 kHz. Mass physical properties of the sediments were determined by conventional techniques. Viscosity was determined with a Brookfield RVT eight speed viscometer. The main instrument array was supplemented by conventional water samplers and corers including a box core.

Table 1. List of sensors mounted on Sediment-Water Interface Probe.

Sensor	Type	Manufacturer	Model
Sediment density	Nuclear transmission gage	Harwell, Great Britain	-
Turbidimeters	Absorption ranges, 0-100, 0-1000, 0-5000 ppm	Partech, Great Britain	-
Pressure	Differential	Bell & Howell	4-351-0054
Current speed	Electromagnetic	Marsh-McBirney	511 & 529

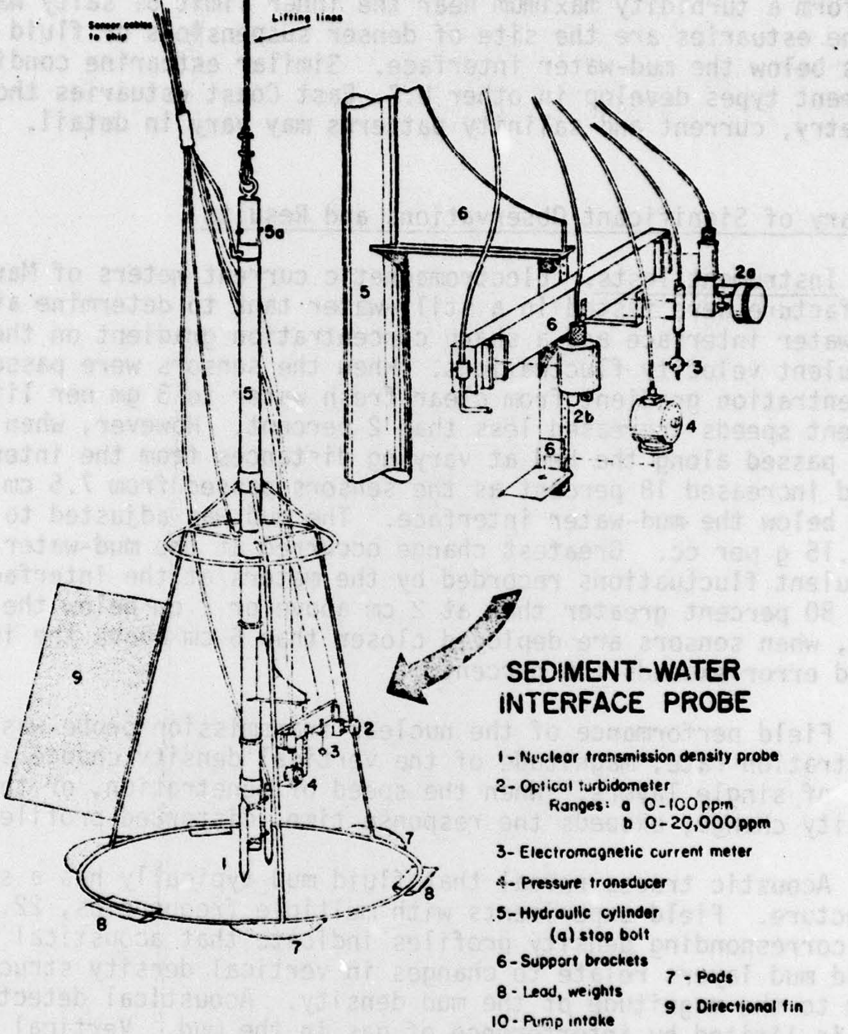

Figure 1. Schematic diagram of the sediment-water interface probe and sensors.

4. Site Description

The James and Rappahannock estuaries and the Upper Chesapeake Bay are transitional zones between fresh-water flows from rivers and the marine environment. The tide, which ranges 35 to 51 cm, produces unsteady quasi-periodic flows with speeds varying from nearly zero at slack water to 65 cm per sec at maximum current. In the transition from river to tide-induced flow, salinity ranges from nearly zero to about 16 ppt and produces a neutrally stratified bottom boundary layer. Wave action was not important at the time of observations.

Sediments transported into landward parts of these estuaries are mainly derived from the river. They are fine-grained, 2 to 16μ particle size, and consist of a heterogeneous mixture of illite, kaolinite and chlorite minerals. Organic matter of the mud is about 1 to 3 percent by dry weight. Concentrations of suspended sediment range about 20 to 300 mg per liter and form a turbidity maximum near the inner limit of salty water. Channels of the estuaries are the site of denser suspensions or fluid mud which forms below the mud-water interface. Similar estuarine conditions and sediment types develop in other U.S. East Coast estuaries though the bed geometry, current and salinity patterns may vary in detail.

5. Summary of Significant Observations and Results

Instrument Tests. Electromagnetic current meters of Marsh-McBirney manufacture were tested in a still-water tank to determine affects of the mud-water interface and a sharp concentration gradient on the speed and turbulent velocity fluctuations. When the sensors were passed through a concentration gradient from clear fresh water to 3 gm per liter, mean current speeds increased less than 2 percent. However, when the sensors were passed along the bed at varying distances from the interface, mean speed increased 18 percent as the sensors passed from 7.5 cm above to 5 cm below the mud-water interface. The mud was adjusted to a density of 1.15 g per cc. Greatest change occurred at the mud-water interface. Turbulent fluctuations recorded by the meters at the interface were more than 80 percent greater than at 2 cm above or 2 cm below the interface. Thus, when sensors are deployed closer than 6 cm above the interface, mean speed error exceeds $\pm$ 5 percent.

Field performance of the nuclear transmission probe was affected by penetration rate, magnitude of the vertical density change and the thickness of single layers. When the speed of penetration, or the vertical density change, exceeds the response time, distorted profiles result.

Acoustic traces reveal that fluid mud typically has a stratified structure. Field experiments with multiple frequencies, 22.5 and 200 kHz, and corresponding density profiles indicate that acoustical detection of fluid mud layers relate to changes in vertical density structure rather than to the magnitude of the mud density. Acoustical detection of fluid mud is limited by interference of gas in the mud. Vertical density profiles of a nuclear density gage provide the most reliable means of defining fluid mud thickness.

Experimental Results. Since fluid mud tends to set itself in motion on a slope, tests were designed to determine the angle of repose and critical slope for movement. Estuary mud of varying density, 1.05, 1.10 and 1.15 g per cc, were introduced onto the bed of a still-water tank at varying slopes, zero, 1:200, 1:100, 1:50, 1:25. When suspensions of 1.05 and 1.10 g per cc were supplied to a slope steeper than 1:100, the mud moved downslope while the final angle of repose was 1:12. At a higher mud density, 1.15 g per cc, a slope steeper than 1:50 was required for movement. By contrast, a static mud of 1.05-1.10 g per cc required a slope of about 1:14 to set itself in motion. In summary, mud having a low solids concentration will flow down a gentle slope whereas mud of high concentrations, which presumably attains a degree of internal cohesion, resists movement of gravity forces and maintains steeper slopes.

Field Observations. Fluid mud was recorded in vertical density profiles throughout channels of the James and Rappahannock estuaries from both freshwater and saline zones. It attains greatest thickness, up to 62 cm, in shipping channels where sedimentation is fast. With a rate of 10 cm per year, it takes 3 to 4 years for fluid mud to dewater and consolidate to a density greater than 1.30 g per cc. Relative large "blanket" deposits 10 to 20 cm thick persist in the turbidity maximum zone near the inner limit of salty water. Most of the deposits examined are static suspensions or settled mud. However, the top millimeter or less may move in response to storm waves or strong tidal currents. The resuspension potential partly depends on mud viscosity.

Viscosity measurements and resulting rheograms reveal that the mud exhibits both a pseudoplastic and a dilatant behavior. During accelerating rates of shear, the apparent viscosity profile decreases to its lowest value and becomes highly variable. By contrast, during decelerating shear, the profile displayed a hysteresis effect. This indicates thixotropic behavior whereby the mud changes its properties, i.e. yield stress, and viscosity. Viscosity decreased more rapidly in mud from low salinity zones (2 to 8 ppt), i.e. the zone of the turbidity maximum, than in mud from high salinity zones or from fresh water. Yield values increased with settling time of the mud being greatest in mud from low salinity zones. The observations show that the resuspension potential of mud in the turbidity maximum zone is greater than in either more saline or in freshwater zones. These data suggest the bed is responsive to shear stresses, either ejecting sediment or resisting shear with time.

Reynolds stress and bed shear stress were derived from times series tidal current measurements of a two component electromagnetic meter. Measurements were made at 6, 15 and 100 cm above the mud-water interface at four stations in the Rappahannock over one tidal cycle. The data were analyzed to obtain mean longitudinal (μ) and vertical (ω) currents and corresponding turbulent fluctuations (μ and ω). The Reynolds stress ranged from nearly zero to about 2.0 dynes per sq cm generated by currents reaching 30 cm per sec. Stress increased linearly with acceleration of mean current. Like bed shear stress, it lagged the maximum current velocity by one to two hours, reflecting the increased turbulence intensity during deceleration of the tidal current. However, there is a high sampling variability. Intermittency of the fluctuations extends upward one meter above the bed where most turbulence is produced.

It is concluded that deposition of fluid mud is controlled by turbulent processes active near the bed. Fresh mud of low viscosity and relatively low shear strength will fail when stress exceeds about 0.8 dynes per sq cm. It is broken into small units which are resuspended by turbulent lift forces. When tidal currents are weak during 3 to 5 days of neap tide range, the mud develops sufficient strength, by attachment of cohesive bonds, to withstand current stress up to 0.8 dynes per sq cm. The mud may be eroded quickly, but deposition of mud masses is a slow process.

6. Publications

"Sticky Muds": Viscosity of Estuarine Sediments, by R. Faas, Abstr. Annual Meet AAPG-SEPM 1979, p. 84.

Rheological Characteristics of Rappahannock Estuary Muds: Applications to North Sea Estuarine Systems, by R. Faas, Pre-print, Intern. Assoc. Sedimentologists, North Sea '79, Texel, Neth., 2p.

7. Participating Personnel

Dr. Maynard Nichols, of Virginia Institute of Marine Science formulated the study in collaboration with Dr. Richard Faas, of Lafayette College. Mr. Galen Thompson, VIMS research assistant directed field operations and laboratory processing; he performed the slope and instrument testing together with Mr. Donald Baker, VIMS research instrument engineer. Cruise preparation, laboratory filtration, instrument calibration and data reduction were accomplished by VIMS technicians T. Vass, E. Clark, A. Evans and students B. Fiest, Kurt Nygaard, Craig Lukin.