Mud consolidation during a short time interval

NATHAN HAWLEY*

Department of Earth and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

ABSTRACT

Flume observations of the consolidation of mud beds deposited from an unsteady flow show that a 10-mm layer undergoes considerable consolidation during the time of deposition and within the first hour after deposition ceases, but little additional consolidation during the next 24 hr. A certain minimum thickness, between 3 and 10 mm, is required for any consolidation to occur. The results support the hypothesis that thick mud layers may form in nearshore subtidal areas as the result of accumulation of thinner layers deposited during successive tidal cycles, but only if each individual layer is able to withstand erosion during the subsequent cycle.

INTRODUCTION

Reineck and Wunderlich [1] have proposed that flaser bedding results from alternating periods of sand and mud (defined as material with an equivalent fall diameter of <60 μm), deposition during tidal cycles, with sand deposited during ebb and flood tides and mud deposited during the slack-water intervals at low and high water. This mechanism requires the deposition of substantial thickness of mud during relatively short intervals (approximately 1 to 6 hr). McCave [2] calculated that suspended sediment concentrations of the order of kg/m^3 are necessary to deposit a 10-mm-thick mud layer in a 4-hr interval. Concentrations of this magnitude may certainly be found in nearshore areas, although they are rare farther offshore; but even if sufficient mud is deposited, it still must consolidate sufficiently to withstand erosion during the subsequent ebb or flood tide. This paper reports on the results of a series of experiments on the deposition and consolidation of mud layers, 10 mm thick, during a single slack-water event. Since the mud layer was submerged at all times, the results are applicable only to subtidal areas. In intertidal areas mud consolidation behavior may be considerably different.

Most experiments on the erosion of mud beds have been done using beds either not deposited directly from suspension [3] or deposited from thick slurries [4,5]. Application of these results to tidal areas is difficult because the consolidation of the mud beds in the experiments, and hence their resistance to erosion, may differ from that found in natural settings. One series of experiments [6] used mud beds deposited from a dilute suspension, but the consolidation time is not reported.

Although the consolidation behavior of mud beds has been investigated by several authors, again it is difficult to apply their results directly to tidal settings because of either very long compaction times [7] or the high suspended sediment concentrations from which the beds were deposited [4,8,9]. To date, the most extensive investigations have been by Migniot [9] and Owen [10], both of whom studied the behavior of thick individual beds deposited in still water. Migniot used a slurry with a density of about 50 kg/m^3 and reported that consolidation occurred in three distinct phases, each with a characteristic logarithmic increase in sediment density with time. The first phase, which lasted about 10 hr and was concurrent with deposition, showed a rapid increase in density as the individual mud flocs were rearranged and compressed due to the weight of the accumulating overburden. During the second phase, which lasted approximately 500 hr, the density increased more slowly as water escaped either through drainage wells, which are

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* Present address: Department of Atmospheric and Oceanic Science, the University of Michigan, Ann Arbor, MI 48109.

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vertical cracks in the mud, or by percolation. In the last phase, when water escaped only by percolation, the density increased at an even slower rate.

Owen [10] performed an extensive investigation using a wide range of suspended sediment concentrations deposited in still water, the two lowest of which (1 and 4 kg/m^3) might be observed in nearshore areas. The thinnest mud bed formed had a maximum thickness of 110 mm 4 hr after the initiation of deposition. Measurements made at this time showed that the mud density remained approximately constant throughout the upper two-thirds of the bed, but increased rapidly near the base. The next measurements, taken about 4 hr later, show a small increase in mean density (15%) and a decrease in density variation with depth. Owen also confirmed the results of Einstein and Krone [8], who showed that the shear strength of mud, which is an index of its resistance to erosion, is directly related to its density.

On the basis of his results, Owen suggested that a thin mud layer, consolidated enough to withstand erosion, could be deposited as the basal part of a thicker layer during a single slack-water period. A thick mud layer could then be formed by the accumulation of several thinner layers deposited during consecutive tidal cycles, although the bulk of the mud deposited during each individual slack-water period would be resuspended. This is similar to the mechanism proposed by Terwindt and Breusers [4] to explain the existence of mud layers 1 to 5 mm thick in the Haringvliet estuary, but not identical, since Terwindt and Breusers [4] suggested that individual mud layers with a total thickness of 3 mm would not be resuspended.

Although Owen's hypothesis may explain the formation of thick mud deposits in areas where large amounts of mud are deposited during each depositional period, it may not be valid if the individual accumulations are less than in his experiments.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Experiments investigating the consolidation behavior of mud beds, approximately one-tenth the thickness of Owen's, were conducted in a recirculating flume 10 m long and 0.15 m wide. Because of the shallow water depth (12 mm) a suspended sediment concentration of 4 kg/m^3 was used. The mud used was a 50%-50% mixture of kaolinite and montmorillonite and was deposited from water with a salinity of 15 ppt. Since the experiments were part of an investigation of flaser bedding, the mud was deposited over a rippled sand bed. The mud was deposited from an unsteady flow described by equation (1):

$$V(\tau) = A[2\sin(\omega\tau) + \sin(2\omega\tau)] \qquad (1)$$

where V is the velocity, $\omega = 2\pi/12.5$ hr, τ is the time, and A is a constant. The maximum velocity was 0.30 m/sec and the slack-water period was 1.25 hr. Further details can be found in Hawley [11].

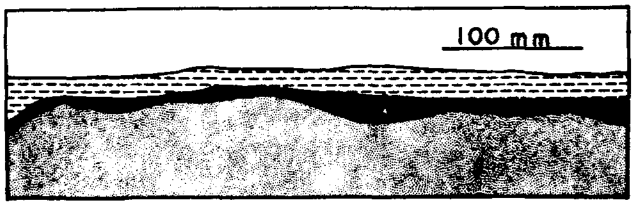

Figure 1. A rippled sand bed (stippled pattern) overlain by an unconsolidated upper mud layer (dashed lines) and a lower consolidated layer (black). Note the drainage wells in the lower layer which form as water is expelled during consolidation.

RESULTS

During each of the two runs the formation of two distinct mud layers was observed at the end of the slack-water period (Fig. 1). The upper layer was subsequently resuspended at low flow velocities (<0.16 m/sec), while the lower layer, which comprised about one-third of the total thickness, resisted erosion at velocities up to 0.24 m/sec, corresponding to a shear velocity of 0.0175 m/sec. The occurrence of these two layers, with their differing resistance to erosion, agrees with Owen's description of the density variation in mud beds, even though his beds were considerably thicker. This, coupled with the observation of drainage wells in the lower layer, suggests that consolidation in these thin beds occurred at rates faster than those observed by either Migniot [9] or Owen [10].

In order to determine whether a longer slack-water interval would result in further consolidation, two additional experiments were carried out in which the mud beds were left undisturbed for 24 hr. The same time-varying current was applied to these beds as to those with the 1.25-hr undisturbed interval. The rates of erosion were found in all cases by measurements of suspended sediment concentration 10 mm above the bed. Figure 2 shows the change in suspended sediment concentration for all four runs. Differences in suspended sediment concentration as a function of time between the two sets are negligible, suggesting that virtually all consolidation had occurred in the first 1.25 hr. The fact that no further thickening of the lower layer was observed during the 24-hr period supports this conclusion. The formation of drainage wells, which are not reported by Owen [10], suggests that consolidation occurred even more rapidly in these experiments than in his, and that a thin mud bed deposited under these conditions, which were chosen to reflect a realistic tidal situation, effectively reaches its maximum consolidation very shortly after deposition.

Additional experiments with an even thinner mud bed (3 mm) revealed that there is a critical accumulation necessary for any significant consolidation to occur. All the 3-mm-thick beds behaved similarly to the upper layers of the thicker beds

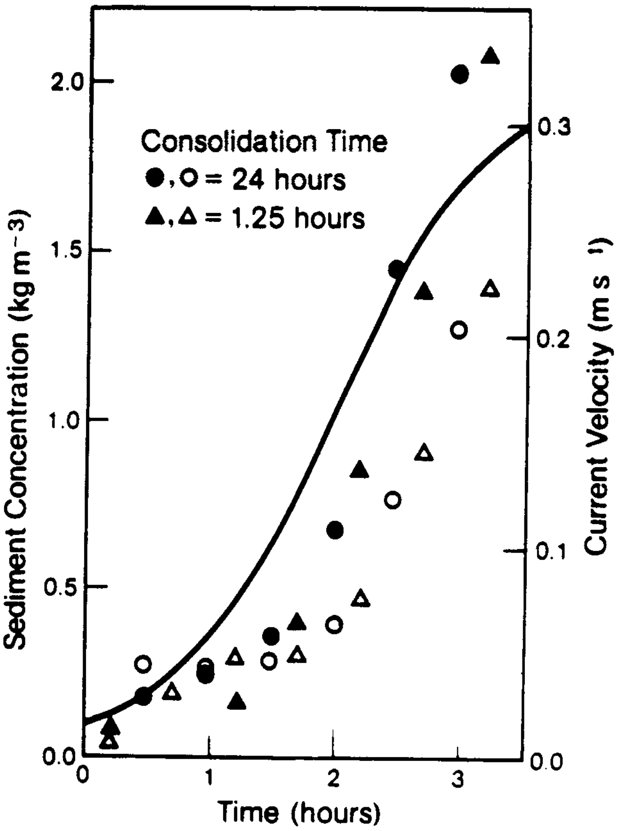

Figure 2. Comparison of the rates of erosion for beds left undisturbed for 1.25 and 24 hr. The line indicates the current velocity.

and were resuspended at velocities <0.24 m/sec. The critical thickness is therefore somewhere between 3 and 10 mm.

DISCUSSION

The consolidation of thin mud layers within 1.25 hr after deposition lends support to Owen's hypothesis for the origin of thick mud beds in tidal areas, and extends his results to thinner beds than he observed. In order to apply the experimental results to natural situations, however, some conversion is necessary.

Applying particle settling rates calculated from data collected in still water will invariably overestimate the rates of deposition from flowing water, but at present there is no alternative, especially for unsteady flows. Because of their porous structure, cohesive aggregates settle slowly. If one assumes a spherical particle with a diameter of 45 μm and a particle density of 1.108×10^{-3} kg/m^{-3}, then, using Stokes' law, a settling rate of 0.1875 m/hr is obtained [12]. Thus for a settling period of 1.25 hr, only the sediment within 0.23 m of the bottom will be deposited; for 4.5 hours, from the lower 0.844 m; and for 6 hr, 1.125 m. Assuming that a larger particle size will increase these numbers somewhat, smaller particles will settle more slowly. Although the slack-water interval was 1.25 hr, it was observed that deposition began as soon as the velocity began to decelerate, giving a total period of deposition of 4.5 hr. It appears then that, as a crude estimate, only those particles within 1 m of the bottom are likely to be deposited during a typical tidal cycle.

The maximum amount of mud deposited during the flume runs was approximately 0.48 kg/m^2. This gives a suspended sediment concentration of 0.48 kg/m^3 needed to produce a mud layer 10 mm thick. Such concentrations are not unusual in many nearshore areas. The difference between this estimate and that of McCave [2] is due mainly to the difference in settling rates used. It appears possible, then, that the formation and consolidation of thin mud layers in nearshore subtidal areas may be more widespread than the data of Owen [10] would indicate.

However, these thin beds will only accumulate into a thicker bed if each individual bed is able to withstand erosion during the subsequent tidal cycle. Only if the tidal currents are relatively weak can a thick mud bed be formed due to the accumulation of several thin beds. In areas where the currents are stronger, the formation of such a bed can occur only if the individual beds are thicker, allowing more consolidation in the basal unit. This in turn requires higher suspended-sediment concentration.

CONCLUSIONS

The experiments support Owen's [10] results and extend them to thinner mud beds and lower suspended sediment concentrations. Thin mud beds consolidate quickly (within 5 hr of the initiation of deposition) provided that a critical thickness (somewhere between 3 and 10 mm) is attained. These observations support Owen's [10] hypothesis that thick mud layers may result from the accumulation of thinner layers deposited during successive tidal cycles. Such a mechanism may only work, however, if each individual layer is capable of withstanding erosion during the ebb or flood tide immediately subsequent to its deposition.

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