RESUSPENSION OF DEPOSITED COHESIVE SEDIMENT BEDS

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ABSTRACT

Surficial layers of estuarial fine, cohesive sediment beds are deposited from flow and often are in a state of partial consolidation. A series of laboratory investigations were carried out to elucidate the erosional behavior of deposited cohesive sediment beds in flumes using kaolinite. A significant feature of such beds is that they are stratified with respect to the density and the cohesive shear stength. Under a given bed shear stress, erosion occurs at a continuously decreasing rate up to a depth at which the bed shear stress equals the shear strength. This bed shear stress is therefore also equal to the critical shear stress for erosion at that depth. An expression for the rate of erosion relating this rate to the difference between the bed shear stress and the critical shear stress has been obtained. The critical shear stress increases both with depth and with the bed consolidation time. The rate of erosion decreases with increasing consolidation time.

INTRODUCTION

The sediment at the bottom and in suspension in most estuaries is typically fine, cohesive in nature (14). Cohesive sediments are comprised primarily of particles in the clay and silt size-range plus organic matter and waste materials. Surficial layers of cohesive sediment beds in estuaries generally consist of partially consolidated material deposited from flow (9). Such layers have a high water content and very low cohesive shear strength which tends to exhibit a non-uniform variation with depth below the bed surface. The shear strength is however too low for it to be measured, for example, with such device as a penetrometer (13). The bed can exhihit two modes of failure. The first, known as surface erosion, involves floc-by-floc rupture and entrainment of the surficial sediment. The second, known as mass erosion, results from a dynamic shear loading of the bed. In this case the plane of failure lies deep in the bed, and failure results in an almost instantaneous entrainment of the sediment above the plane. Under typical estuarial environment, erosion occurs predominantly at the surface and is considered here. Until recently,

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the erosional behavior of deposited beds was not investigated adequately (9). Attempts to relate the rate of erosion with standard soil indices such as the Atterberg limits were unsuccessful because these indices do not properly account for the resistance to erosion which essentially depends upon the strength of the inter-particle electro-chemical bonds (12, 14). Resistance to erosion must be characterized by physico-chemical parameters, some of which have been identified more recently (8).

Laboratory investigations were carried out at the University of Florida in order to investigate the erosional behavior of deposited cohesive sediment beds. The main findings are summarized below. Details are given elsewhere (1, 7, 11, 16).

APPROACH

The rate of surface erosion, ε, expressed as the mass of sediment eroded per unit bed area per unit time, is related to the time-rate of change, dz/dt, of the depth of erosion, z, below the initial bed surface according to:

$$\varepsilon = h\frac{dC}{dt} \tag{1}$$

$$\frac{dC}{dt} = \frac{\rho(z)}{h}\frac{dz}{dt} \tag{2}$$

where h = depth of flow, dC/dt = time-rate of change of suspended sediment concentration, C, and $\rho(z)$ = depth-varying dry density of the bed. Several investigators measured the variation of dC/dt with time t for deposited beds in a closed system and observed that, under a constant bed shear stress, τ_b, dC/dt (and therefore ε) generally decreases continuously with t, beginning with a relatively high value when erosion commences (9). For a certain range of τ_b and "large" t ranging from a fraction of an hour to several hundred hours depending upon the type of fluid-sediment mixture and the magnitude of τ_b, the rate of erosion, ε, becomes equal to zero or approaches zero. In other words, C becomes constant or approaches a constant value asymptotically. Given the bed density distribution $\rho(z)$, the magnitude of the constant value of C and the rate of approach of C to this value depend upon τ_b (which defines the erosive force), and upon parameters which characterize the resistance to erosion. Important among the latter is the cohesive shear strength of the bed with respect to erosion.

In the reported studies, resistance to erosion was varied by two means: 1) by varying the conditions for bed preparation, and 2) by varying the salinity of the fluid. Time-concentration data obtained under a wide range of τ_b values have been used together with the bed density in order: 1) to elucidate the mechanics of the resuspension behavior of deposited beds, and 2) to obtain an expression for the rate of erosion in terms of the bed shear stress and parameter(s) characterizing resistance to erosion.

APPARATUS AND MATERIAL

The experiments were performed in two flumes: a rotating annular flume and a flow recirculating flume. The two main components of the annular flume (Fig. 1) are: an annular fibreglass channel (0.21 m wide, 0.46 m deep, and 1.5 m in mean diameter) containing the fluid-sediment mixture, and an annular ring of slightly smaller width positioned within the channel and in contact with the fluid surface. A simultaneous rotation of the two components in opposite directions generates a uniform turbulent flow field free from floc-disrupting elements such as pumps and diffusors in which very high shearing rates generally prevail. By a proper adjustment of the speeds of the two components the rotation-induced secondary currents are eliminated, and the distribution of the bed shear stress across the channel width is found to be uniform (5). The steel recirculating flume, open at the top (Fig. 2), is 18 m long, 0.6 m wide and 0.9 m deep, with an underflow-type control gate at the downstream end. The return pipe diameter is 0.2 m. One side of the flume is made of glass panels for visual observations (1).

A commercial kaolinite with a cation exchange capacity of approximately 12 milliequivalents per hundred grams was used in all tests. The median diameter of the deflocculated sediment was 1 micron, with a range of 0.2 to 40 microns. The fluids were: 1) distilled water as well as salt water of 35 ppt concentration using commercial grade sodium chloride in the annular flume, and 2) tap water with a very low total salt concentration of 0.28 ppt as well as salt water of 35 ppt concentration in the recirculating flume. Kaolinite readily flocculates even in distilled water. The sediment was equilibrated with the fluid for atleast two weeks prior to each test series. The depth of flow was maintained at 31 cm in the annular flume and 23 cm in the recirculating flume. Fluid temperature varied with the ambient. The mean was approximately 26°C.

EXPERIMENTS AND RESULTS

There were four experimental series. These are described in the order in which they were performed.

Series 1 Experiments

These experiments were carried out in the annular flume using kaolinite in distilled water (7). Two types of beds were used: the first was deposited gradually from suspension while the flume was in motion and the bed shear stress was kept slightly less than τ_{bmin}, i.e., the shear stress at which the entire amount of initially suspended sediment deposits eventually (6). The second was prepared outside the flume at a density close to that of the deposited sediment and subsequently placed and leveled into the flume. The main difference between these two beds was with respect to the vertical distribution of their cohesive shear strength. In the formation of the first bed there was a preferential deposition whereby larger and more cohesive flocs deposited first while the smaller, less cohesive flocs deposited later. For this reason the first bed may be referred

Fig. 1. A View of the Annular Rotating Flume.

Fig. 2. A View of the Open, Flow Recirculating Flume.

to as stratified, a situation commonly encountered in estuaries. In contrast, the second bed may be termed uniform, since it had practically constant properties in the vertical direction.

Figure 3 shows the time-concentration relationship for the case of a stratified bed eroded under a shear stress $\tau_b = 0.207$ Nm^{-2}. The ordinate gives the suspended sediment concentration as a fraction of the total dry weight of the bed material. It is observed that the slope of the curve, i.e., the erosion rate, decreased with time and became nearly zero at the end of the test. This observation is in agreement with the erosion test results of Partheniades (13) with a bed composed of natural, flocculated, silty-clay from the San Francisco Bay and deposited in an open flume at low velocity. The predominant clay mineral of that sediment was montmorillonite with some illite.

Figure 4 shows an erosion test for a uniform bed under a shear stress of 0.413 Nm^{-2}. Two additional tests were carried out at shear stresses of 0.445 and 0.483 Nm^{-2}. The results were similar to those shown in Fig. 4. Inasmuch as four sample taps at four different elevations were used and since a vertical concentration gradient was generally present in the suspension, a spread of data is observed during certain times. The solid line represents the mean curve. After a relatively short period, the slope of the line, and, therefore, the rate of erosion, became constant. The same was true of the two other tests. The corresponding erosion rates, ε, were 2.03×10^{-6}, 2.64×10^{-6} and 2.92×10^{-6} g cm^{-2} min^{-1}. These rates, when appropriately non-dimensionalized and plotted against the corresponding bed shear stress also in the non-dimensional form, agreed with the earlier results of Partheniades (7, 13).

Two important observations may be made: 1) with reference to the results of the experiment with the uniform bed (Fig. 4), the observed constancy of the rate of erosion implies that the eroded material did not redeposit, since simultaneous erosion and deposition would ultimately result in a state of equilibrium in which the rates of erosion and deposition are equal, and the suspended sediment concentration attains a constant value (6, 13, 14). The absence of exchange of material between the fluid and the bed during erosion under a constant bed shear stress was noted previously by Partheniades (13). In this context it may be noted that flow turbulence varies in the vertical direction from the bed to the surface. Close to the bed a zone of high shear prevails. In the remainder of the flow the shear is relatively much lower. Depending upon the size and the strength of a settling floc at a given instant and the corresponding instantaneous value of the near-bed shear, the floc may deposit, i.e. stick to the bed, or may rupture, with the pieces re-entrained above the near-bed zone. Absence of exchange precludes deposition but not the process of settling and re-entrainment. 2) in the absence of exchange, the attainment of a constant value of the concentration in the case of the stratified bed may be explained by noting that constancy of the concentration occurs when bed erosion is arrested. This is the case because the shear strength increases with depth below the initial bed surface so that no erosion will occur below the depth at which the bed shear stress equals the shear strength.

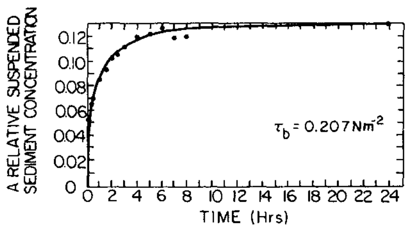

Fig. 3. Relative Suspended Sediment Concentration against Time, t, for a Stratified Bed using Kaolinite in Distilled Water at τ_b = 0.2D7 Nm^{-2}.

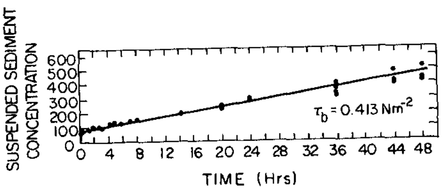

Fig. 4. Suspended Sediment Concentration, C, against Time, t, for a Uniform Bed using Kaolinite in Distilled Water at τ_b = D.413 Nm^{-2}.

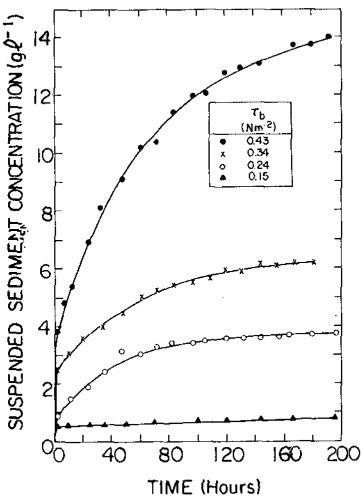

Fig. 5. Suspended Sediment Concentration, C, against Time, t, for a Deposited (Stratified) Bed using Kaolinite in Salt Water at Four Values of τ_b.

Series 2 Experiments

In these experiments, kaolinite in distilled water as well as in salt water was used in the annular flume (16). Stratified beds were prepared in a manner similar to that noted under Series 1 experiments. An example of the results from tests using distilled water is shown in Fig. 5. At the beginning of each test, an almost instantaneous and significant rise in the suspended sediment concentration was noted. It was concluded that this was partly due to mass erosion resulting from a sudden movement of the flume at start. In later experimental series, this problem was obviated by starting the flume more slowly. After nearly 200 hours, whether or not the suspended sediment concentration, C, attained a constant value is observed to have been dependent upon the magnitude of τ_b. In the test with $\tau_b = 0.15\ Nm^{-2}$, C became constant within the first few hours. In the test with $\tau_b = 0.24\ Nm^{-2}$, C became constant after approximately 140 hours. In the test with $\tau_b = 0.34\ Nm^{-2}$, C appears to have approached a constant value after 180 hours. Finally, in the test with $\tau_b = 0.43\ Nm^{-2}$, C was increasing with time at a slow rate even after 190 hours. In general, at any instant after test initiation both the magnitude of C and dC/dt (and therefore ε) are observed to vary with τ_b.

Selecting C_s as the asymptotic value of C which was close to the value of C extrapolated to 200 hours, it was found that most of the time-concentration data, after accounting approximately for the mass erosion effect, agreed with the following relationship:

$$C = C_s(1 - e^{-\beta t}) \tag{3}$$

where β is an empirical coefficient whose value was found to be within a relatively narrow range of 0.013 to 0.028 hr^{-1}, particularly for comparatively high values of τ_b. An example of the agreement between Eq. 3 and the experimental values is shown in Fig. 6 for the tests corresponding to Fig. 5. Tests using kaolinite in salt water confirmed these trends. Further tests using a natural mud in salt water also agreed with Eq. 3. The clay mineral constituents of this mud were kaolinite, montmorillonite and illite.

The observed variation of the asymptotic value of C with τ_b may be examined qualitatively with reference to the descriptive relationship between the shear strength, τ_s, and the depth z below the bed surface shown in Fig. 7. As confirmed by experimental evidence presented later, τ_s in a stratified bed increases with z, beginning with a small but finite value close to the surface. This increase is more significant in the top layer of perhaps a few millimeter thickness than in lower layers, where, infact, τ_s may approach a constant value or, atleast, the variation of τ_s with z becomes relatively small. For a given sediment-fluid mixture, the nature of the $\tau_s(z)$ distribution is determined by the flow conditions during deposition, the degree of consolidation of the bed and thixotropic rearrangement of the interparticle floc network (7). Given such a distribution of $\tau_s(z)$, under a bed shear stress τ_{bA} the bed will erode to a depth z_A at which point $\tau_{bA} = \tau_{sA}$. The rate of erosion therefore depends on the "excess" shear stress $\tau_b - \tau_s$. Similarly, if the shear stress is

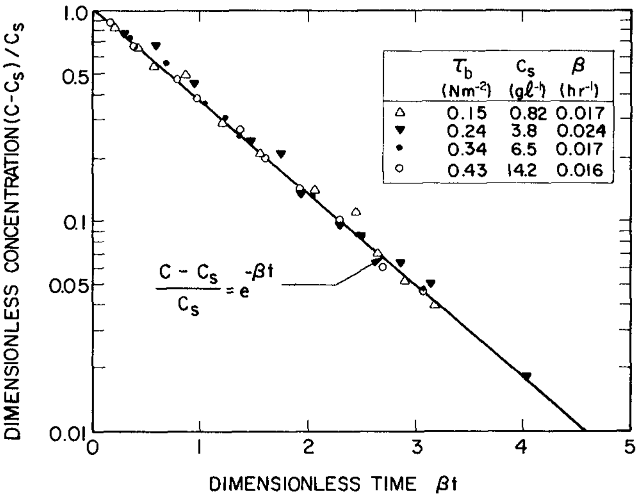

Fig. 6. Normalized Concentration, C_s-$C(t)/C_s$, against Normalized Time, βt. Equation 3 is Compared with Data from Tests Corresponding to Fig. 5.

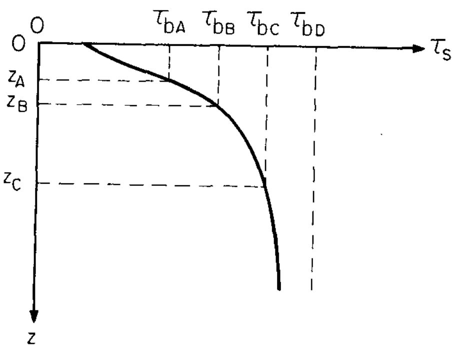

Fig. 7. Descriptive Relationship between Cohesive Bed Shear Strength with Respect to Erosion, τ_s, and Depth, z, below Bed Surface.

τ_{bB} or τ_{bC}, the corresponding depths of erosion will be z_B or z_C. Integrating Eq. 2 yields

$$C = \frac{1}{h} \int_0^z \rho(z)dz \tag{4}$$

provided h is assumed to be constant. Since ρ also increases with z, the difference between C_C and C_B will be much greater than the difference between C_B and C_A. This aspect is further noted later. Finally, for a shear stress τ_{bD}, the bed will continue to erode indefinitely, atleast in principle, since the condition $\tau_{bD} = \tau_{sD}$ can not be attained. In a test conducted by Krone (4) using a silty-clay from San Francisco Bay, erosion continued even after 500 hours.

Series 3 Experiments

These experiments were conducted in the annular flume using kaolinite in salt water. A schematic description of the manner in which the bed shear stress was varied with time during the tests is shown in Fig. 8. Such a variation results in three phases of sediment transport. Phase I is a mixing stage in which a sediment of concentration C_0 is mixed at a shear stress τ_m for a period T_m. The shear stress τ_m must be large enough to prevent any deposition of the suspended material. In Phase II the flow is reduced to yield a comparatively lower shear stress τ_{d1}, which is maintained for a duration T_{d1}. Deposition will occur in this phase. Given a sufficient duration T_{d1} and shear stress $\tau_{d1} < \tau_{bmin}$, the entire amount of sediment will deposit and the flow will be clarified. On the other hand, if $\tau_{d1} > \tau_{bmin}$, a certain fraction C^*_{eq} of C_0 will remain in suspension indefinitely (6). In the latter case, a second lowering of the shear stress to $\tau_{d2} (< \tau_{bmin})$ for a period T_{d2} will clarify the suspension. The last sequence in Phase II is a period T_{dc} with no flow. During this period the remaining small fraction of the sediment in suspension will deposit rapidly and the bed will consolidate. Phases I and II together define the pre-erosion stress history of the bed, which is characterized by C_0, τ_m, τ_{d1}, τ_{d2}, T_m, T_{d1}, T_{d2} and T_{dc}. In order to investigate the influence of consolidation on the rate of erosion, T_{dc} was varied while maintaining all other parameters nearly constant.

Resuspension will occur in Phase III in which a series of shear stresses τ_{b1}, τ_{b2} etc., of increasing magnitudes are applied over corresponding durations (time-steps) T_1, T_2 and so on. In choosing the magnitudes of τ_{b1}, τ_{b2} etc., it is convenient to select the normalized differential shear stress $\Delta\hat{\tau}_{bi} = (\tau_{bi+1} - \tau_{bi})/\tau_{bi}$, where i = 1, 2, etc., as an experimental parameter. The selection of $\Delta\hat{\tau}_{bi}$ and the corresponding period T_i is an important factor in experimental design (11).

As an example of the results, the time-concentration relationship obtained during a test is shown in Fig. 9. Values of the various parameters selected for the test are given in the figure. The shear stress τ_{d1}, was less than τ_{bmin} (= 0.15 Nm^{-2}). During each time-step

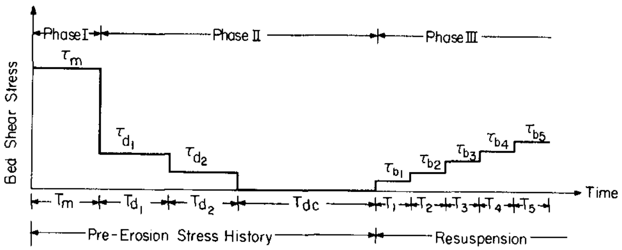

Fig. 8. Schematic Representation of the Variation of Bed Shear Stress, τ_b, during Bed Preparation and Resuspension Tests in Experimental Series 3 and 4.

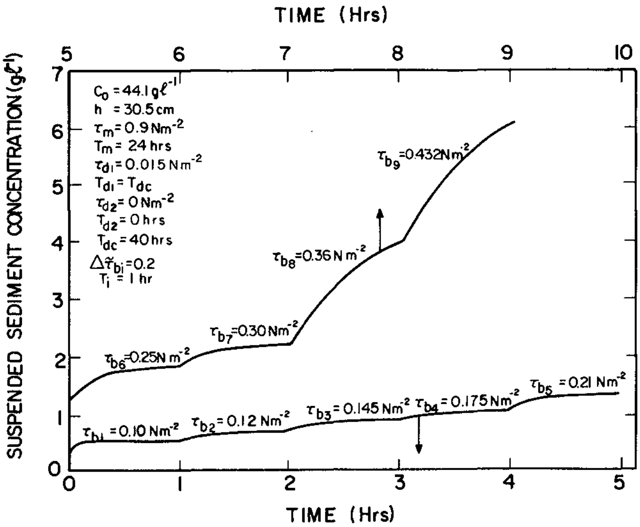

Fig. 9. Variation of Suspended Sediment Concentration, C, with Time, t, during a Test using Kaolinite in Salt Water Following the Approach Schematized in Fig. 8.

i, the rate of erosion decreased from an initially high value, as noted in the previous two experimental series. This trend was found to be qualitatively similar to that suggested by Eq. 3. An important difference between the profiles in steps i = 1 through 7 and steps i = 8, 9 is that in the former (which will be referred to as Type I), the concentration appears to have approached a constant magnitude, whereas in the latter (Type II), the concentration did not attain a constant value at the end of the time-step. This difference between Type I and Type II profiles is also apparent from Fig. 10, in which $C(T_i)$, the concentration at the end of the time-step, i, is plotted against τ_{bi}, for consolidation times T_{dc} = 24, 40 and 135 hrs. In general it appears to be possible to represent the $C(T_i) - \tau_{bi}$ curve by two straight lines meeting at a point where $\tau_{bi} = \tau_{ch}$, a characteristic value of the bed shear stress (11). When $\tau_{bi} > \tau_{ch}$, $C(T_i)$ increases more rapidly with τ_{bi} than in the case when $\tau_{bi} < \tau_{ch}$. The value τ_{ch} also increases with T_{dc}. Similar trends can be discerned from the data presented in Fig. 5 as well as from the results of a number of previous investigations (2). The significance of these trends can be recognized with reference to Fig. 7. In qualitative terms, τ_{bA} and τ_{bB} are both less than τ_{ch}, while τ_{bC} and τ_{bD} are greater than τ_{ch}. The value τ_{ch} lies somewhere between τ_{bB} and τ_{bC}, and the corresponding depth of erosion is between z_B and z_C. Since the increase in the shear strength, τ_s, with z is more significant in the range of $\tau_b < \tau_{ch}$ in comparison with the range of $\tau_b > \tau_{ch}$, if erosion is allowed to proceed for a constant duration T_i under a given bed shear stress, the amount of bed scour will be much greater when $\tau_b > \tau_{ch}$ than when $\tau_b < \tau_{ch}$. Consequently, the rate of change of $C(T_i)$ with τ_b will be much more pronounced in the range of $\tau_b > \tau_{ch}$ in comparison with the range of $\tau_b < \tau_{ch}$.

The above explanation can be used to examine the difference between Type I and II time-concentration profiles in Fig. 9. As long as the condition represented by the shear stress τ_{bD} in Fig. 7 is not attained, i.e. as long as the shear strength $\tau_s < \tau_b$ at some depth z, it is possible to obtain Type I profiles. This may be achieved by increasing T_i, i.e. the time allowed for erosion under a constant bed shear stress. Type II profiles result because T_i is insufficient for the bed to scour to a depth where $\tau_b = \tau_s$.

For Type I profiles, since the condition $\tau_b = \tau_s$ is attained, the depth-variation of τ_s can be determined, provided the depth z of erosion at the end of each time-step i (when $\tau_b = \tau_s$ for that time-step) is known. This can be done using Eq. 2 if $\rho(z)$ is known. The variation of the bed density with depth at the end of Phase II, i.e. just prior to resuspension, was determined for various periods, T_{dc}, with the help of a specially designed 2.5 cm diameter metal tube in which the bed core samples were frozen in situ, using a mixture of alcohol and dry ice (11). These tests were carried out in a separate series in which conditions in Phases I and II were identical to those for the resuspension tests. Figs. 11a,b present the density profile and the corresponding variation of τ_s with depth for the test shown in Fig. 9. The $\tau_s(z)$ distribution is qualitatively similar to the description of Fig. 7. The value of τ_s at z = 0 corresponds to the minimum value of the bed shear stress required to initiate erosion in

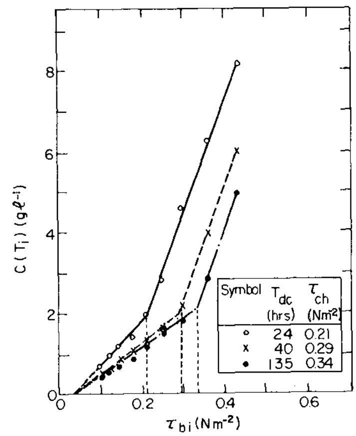

Fig. 10. Concentration, $C(T_i)$, against Corresponding Bed Shear Stress, τ_{bi}, for Three Tests using Kaolinite in Salt Water at Three Values of Consolidation Time, T_{dc} (9).

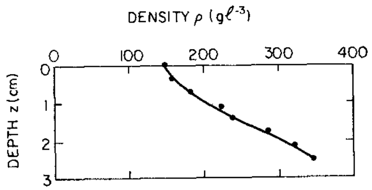

Fig. 11a). Variation of Bed Density, ρ, with Depth, z, in Test Corresponding to Fig. 9.

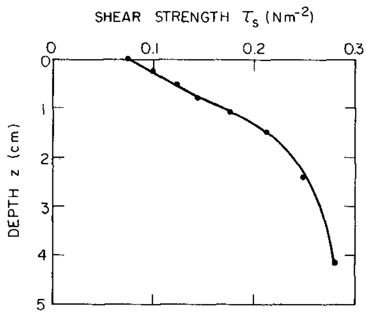

Fig. 11b). Variation of Bed Shear Strength, τ_s, with Depth, z, in Test Corresponding to Fig. 9.

the flume. Indeed as noted further in the following, τ_s obtained in this way is, in general, also equal to the critical shear stress for erosion at the corresponding depth.

Series 4 Experiments

These experiments were similar to those conducted under Series 3. Kaolinite in tap water was used in the recirculating flume (1). Test characterizing parameters were: C_0 = 21.7-24.1 gl^{-1}, h = 23 cm, τ_m = 0.46 Nm^{-2}, T_m = 4 hr, τ_{d1} = 0.026 Nm^{-2} (which was less than τ_{bmin} = 0.18 Nm^{-2}), T_{d1} = 12 hr, τ_{d2} = 0 Nm^{-2}, T_{d2} = 1 hr, $\Delta\hat{\tau}_{bi}$ = 0.52 and T_i = 1 hr. Nine tests with values of T_{dc} = 2, 5, 11, 24, 48, 72, 96, 144 and 240 hr were conducted.

Figures 12a,b are normalized plots of bed density variation with depth. After T_{dc} = 48 hr, the variation seems to conform to the dimensionless relationship (1, 9):

$$\frac{\rho}{\bar{\rho}} = \zeta \left(\frac{z'}{H}\right)^{-\xi} \tag{5}$$

where z' = H-z, H = bed thickness, $\bar{\rho}$ = value of ρ averaged over H, ζ = 0.794 and ξ = 0.288. It is observed that H decreased and $\bar{\rho}$ increased with increasing T_{dc}. Equation 5 is in agreement with the reanalyzed data of Owen (10) and of Thorn and Parsons (15) for four natural muds which gave ζ = 0.660 and ξ = 0.347 (1).

The time-concentration data were found to exhibit a trend which was qualitatively similar to that shown in Fig. 9. These data were analyzed as follows: 1) it was assumed, as noted before, that at the end of time-step i of the Type I profile, the bed shear stress $\tau_b = \tau_c = \tau_s$, where τ_c is defined as the critical shear stress for erosion. 2) using this assumption the variation of τ_c with z was obtained as in Fig. 11b. 3) a relationship between the rate of erosion, ε, and the normalized excess shear stress $(\tau_b-\tau_c)/\tau_c$ was empirically derived from the time-concentration variation for each time-step of the Type I profiles. In obtaining this relationship, ε was calculated using Eq. 1 for each value of dC/dt. The corresponding value of τ_c was obtained using Eq. 2 together with the $\rho(z)$ distribution (Figs. 12a,b or Eq. 5 for $T_{dc} \geqslant 48$ hr) and $\tau_c(z)$ distribution (e.g. Fig. 11b). Finally, 4) it was assumed that the rate expression was applicable over the entire depth of erosion. The time-concentration data of Type II profiles were then used, together with representative depth-mean values of the coefficients (ε_0 and α as noted below) of the rate expression based on Type I profiles, to determine the variation of τ_c with depth z below the depth where this information could not be obtained from Type I profiles. The erosion rate expression was found to be:

$$\frac{\varepsilon}{\varepsilon_0} = \exp\left[\alpha \frac{\tau_b-\tau_c}{\tau_c}\right] \tag{6}$$

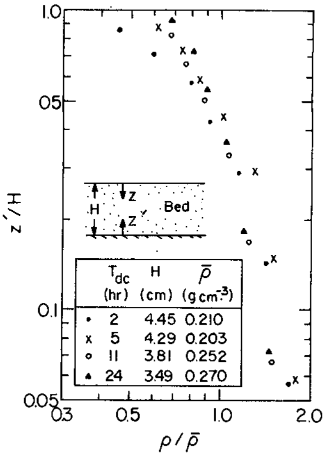

Fig. 12a). Normalized Bed Density, $\rho/\bar{\rho}$, against Normalized Depth, z'/H, for Kaolinite in Tap Water with T_{dc} < 48 hr (9).

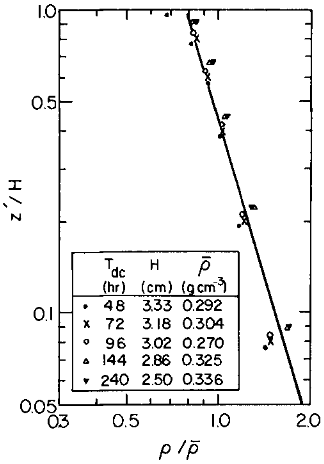

Fig. 12b). Normalized Bed Density, $\rho/\bar{\rho}$, against Normalized Depth, z'/H, for Kaolinite in Tap Water with T_{dc} $\geq$ 48 hr (9).

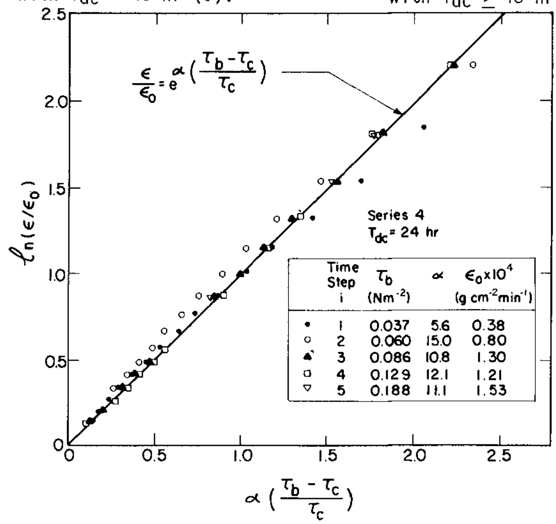

Fig. 13. ϵ/ϵ_0 against $\alpha(\tau_b-\tau_c)/\tau_c$ for a Test using Kaolinite in Tap Water with T_{dc} = 24 hr.

where ε_0 and α are empirical coefficients. In Eq. 6, τ_c is a function z and, therefore varies with time t. With increasing time, τ_c increases and approaches τ_b in such a manner that the ratio $(\tau_b-\tau_c)/\tau_c$ decreases and, therefore, ε decreases. As an example, in Fig. 13 Eq. 6 has been compared with test results corresponding to T_{dc} = 24 hr. The value of α ranged from 5.6 to 15.0 and ε_0 from $0.38\text{x}10^{-4}$ to $1.53\text{x}10^{-4}$ g cm^{-2} min^{-1}. Similar results from tests with T_{dc} = 48 and 240 hr are shown in Figs. 14 and 15. In Fig. 16, reanalyzed data from the test shown in Fig. 9 under Series 3 experiments are plotted in the same manner. In this case, α ranged from 5.5 to 8.4, and ε_0 from $0.04\text{x}10^{-4}$ to $0.30\text{x}10^{-4}$ g cm^{-2} min^{-1}. It was, in general, found that in each test, ε_0 and α appeared to vary somewhat with the time-step, and therefore with depth z below the bed surface, in a systematic manner. Further investigations are required for elucidating the precise nature of the dependence of ε_0 and α on z. In general it was noted that ε_0 and α became nearly independent of z for depths greater than a few millimeters. These two coefficients were also found to be independent of consolidation time, T_{dc}. In Fig. 17, the depth-average value $\bar{\varepsilon}_0$ of ε_0 from each test is plotted against the corresponding T_{dc}. Results from Series 3 (kaolinite in salt water) as well as Series 4 (kaolinite in tap water) are included. In Fig. 18 a similar plot is given for α. Overall mean values of ε_0 and α are: $7.9\text{x}10^{-5}$ g cm^{-2} min^{-1} and 9.3, respectively, for kaolinite in tap water (Series 4) and $4.0\text{x}10^{-5}$ g cm^{-2} min^{-1} and 5.9, respectively, for kaolinite in salt water (Series 3). The mean ε_0 and α for kaolinite in tap water are higher than for kaolinite in salt water. These differences imply that kaolinite is resuspended with greater facility in tap water than in salt water. This trend appears to be consistent with the flocculation characteristics of kaolinite in the two fluids (5, 6, 9).

As an example of the variation of τ_c with depth z, Fig. 19 shows results from four tests with T_{dc} = 2, 11, 48 and 144 hr. In general, τ_c increased with T_{dc} for all $z > 0$. The value of τ_c remained practically invariant at the surface. This observation is in agreement with a similar observation made by Partheniades (13). As a result of the exponential form of Eq. 6, the significance of the variation of τ_c with T_{dc} is that the rate of erosion, ε, decreases measurably with increasing value of T_{dc}.

The form of Eq. 6 has been predicted previously from a reinterpretation of the rate process theory of chemical reactions (1, 3, 12). This theory involves the activation energy concept according to which a "threshold" energy barrier must be crossed for the conversion of reactants to products. As Paaswell (12) has noted, Eq. 6 makes possible the understanding of erosion as an internal energy/external energy system, where ε is a measure of the work done on the system (reflected in τ_b) and τ_c, α and ε_0 represent measures of internal energy, and therefore the resistance to the erosion of the deposit.

CONCLUSIONS

1. The rate of surface erosion of stratified, deposited beds continuously decreases with time and can even become zero as the

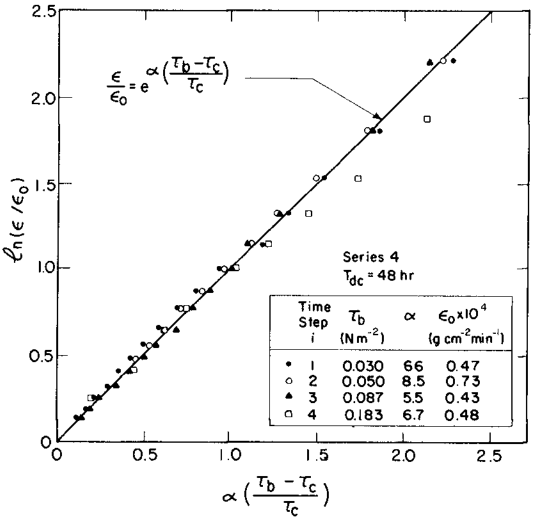

Fig. 14. ϵ/ϵ_0 against $\alpha(\tau_b-\tau_c)/\tau_c$ for a Test using Kaolinite in Tap Water with T_{dc} = 48 hr.

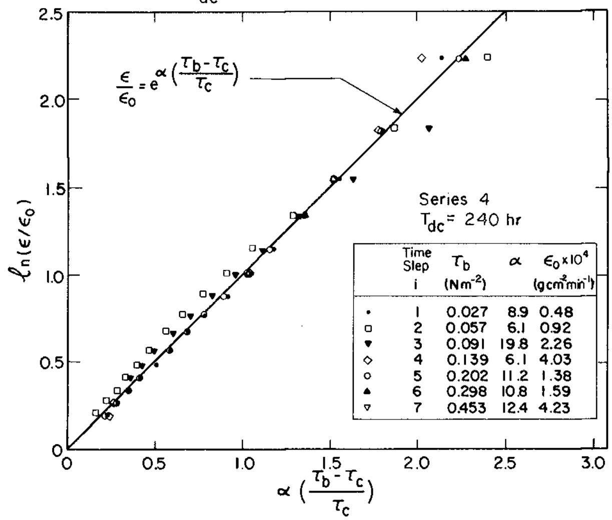

Fig. 15. ϵ/ϵ_0 against $\alpha(\tau_b-\tau_c)/\tau_c$ for a Test using Kaolinite in Tap Water with T_{dc} = 240 hr.

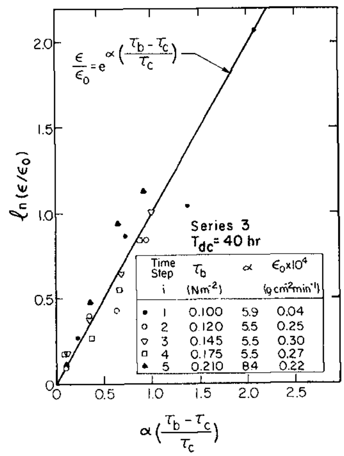

Fig. 16. $\varepsilon/\varepsilon_0$ against $\alpha(\tau_b-\tau_c)/\tau_c$ for a Test Corresponding to Fig. 9.

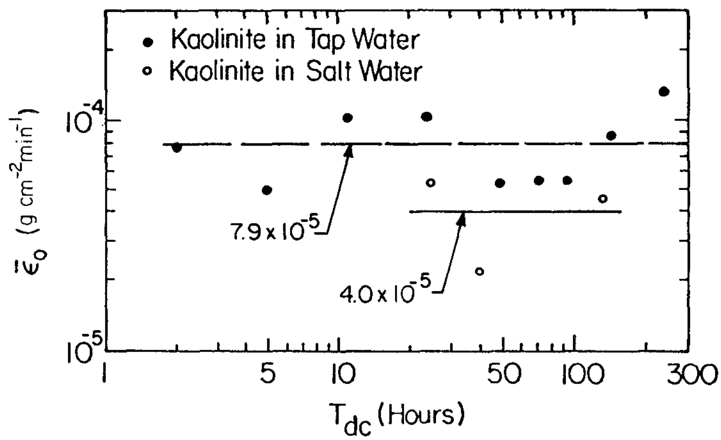

Fig. 17. $\bar{\varepsilon}_0$ against T_{dc} from Tests with Kaolinite in Salt Water and with Tap Water (9).

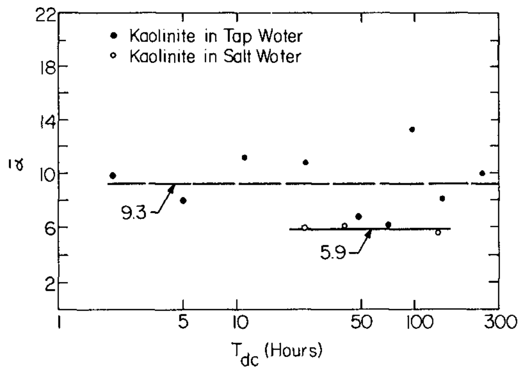

Fig. 18. $\bar{\alpha}$ against T_{dc} from Tests with Kaolinite in Salt Water and with Tap Water (9).

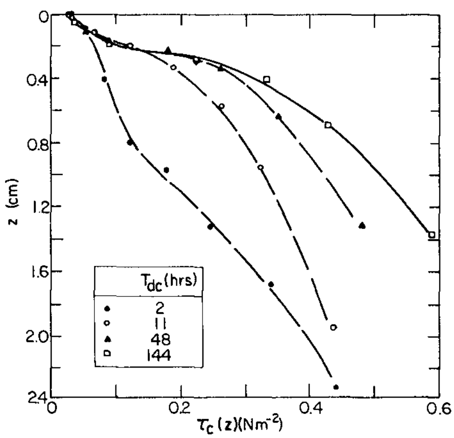

Fig. 19. Variation of τ_c with z from Tests using Kaolinite in Tap Water with T_{dc} = 2, 11, 48 and 144 hr.

depth of erosion increases. On the other hand, the erosion rate of uniform beds remains practically invariant.

2. The decrease in the erosion rate of stratified beds occurs because the cohesive shear strength with respect to erosion of the bed increases with depth. During erosion flocs are detached from the bed and entrained, but redeposition of the entrained sediment does not occur. Erosion is arrested at a depth where the bed shear stress, τ_b, equals the bed shear strength. This value of τ_b is equal to the critical shear stress, τ_c, of the bed at that depth.

3. An expression for the rate of surface erosion is found. The rate varies exponentially with the normalized excess shear stress, $(\tau_b-\tau_c)/\tau_c$.

4. The critical shear stress in general increases with depth below the initial bed surface and also increases with bed consolidation time. As a result the rate of erosion decreases with increasing consolidation time.

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