Jurnal Kejuruteraan 9 (1997) 1-13

A Study on Erosion of Soft Sediment Deposits

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ABSTRACT

Erosional pattern of fine cohesive sediment must be defined to predict the transport model in estuarial water. Resistance to erosion is largely dependant on physico-chemical properties of sediment and fluid, as well as the interparticle bond which is characterized by shear strength. Successively incremental flow-induced bed shear stress is applied to initiate layer by layer erosion of soft cohesive sediment deposit to determine the rate of erosion. A decrease in erosion rate is observed at the end of each time step. This behavior is due to the increasing shear strength with depth. The rate of erosion was found to vary exponentially with cubic root of excess bed shear stress $\left(\tau_b - \overline{\tau_s}\right)^{1/3}$.

ABSTRAK

Bentuk hakisan pada endapan jeleket halus mesti ditentukan untuk mengagak bentuk pergerakan endapan di muara. Halangan pada hakisan adalah terutamanya bergantung kepada sifat fizikal-kimia endapan dan bendalir, di samping ikatan antara partikel yang ditunjukkan oleh kekuatan ricih. Daya ricih yang dihasilkan oleh aliran bendalir, dan yang juga meningkat pada kadar yang sama, dikenakan ke atas lapisan lumpur untuk menghasilkan hakisan lapisan demi lapisan lumpur tersebut. Ini untuk menentukan kadar hakisan. Pengurangan kadar hakisan diperhatikan pada setiap langkah. Kelakuan ini adalah disebabkan oleh peningkatan kekuatan ricih berbanding kedalaman. Kadar hakisan ditemui adalah berkadaran secara eksponen dengan punca kuasa tiga daya ricih lapisan dasar $\left(\tau_b - \overline{\tau_s}\right)^{1/3}$.

INTRODUCTION

Erosion of soil from land masses has been the area of interest for the past more than half a century. Basic research on properties and behavior of low strength estuarial clay deposit under flow-induced bed shear stresses has been carried out recently.

In an estuarial deposit, two modes of erosion can be observed under flow-induced bed shear stresses (Mehta 1984). At bed shear stress just above critical value, erosion proceeds by rupturing the interparticle bonds and surface erosion occur. When bed shear stress exceed the bulk shear strength, relatively large portions of bed are ripped off and entrained in a flow and this is known as mass erosion.

To initiate erosion, interparticle bonds of the surfacial particles must be broken i.e. the shear stress must exceed some minimum shear strength value.

The factors affecting interparticle forces are clay type, electrolytic concentration and exchangeable cation. To consider all of these factors and interdependency in a single study is almost impossible due to the unpredictable hydrodynamic environment. Therefore, the flow-induced bed shear stresses in the water-sediment interface would be a good representative measure to the entrainment force (Ariathurai & Krone 1976).

The main purpose of this study is to investigate the erosional pattern of locally collected natural mud and kaolinite. As physico-chemical factors are influential in the erosional process, the effect of salinity and consolidation period were also observed.

EXPERIMENTAL CONSIDERATIONS

APPARATUS

A straight recirculating tilting flume was used for the present study. It is a 23 m long, 0.6 m deep and 0.25 m wide steel flume. Both sides of the flume is furnished with 12 mm clear plexiglass sheet for visual observation. The main flume structure is laid on two parallel 12 inches I beam and they are uphold by a bearing support and a hydraulic jack system. The maximum longitudinal slope provided by the jack is 0.018. A 200 mm diameter pipe assembly and a 1.0 m × 1.0 m × 1.5 m sump is connected with the whole system to ensure a complete recirculation of saline water. The experimental bed section is 5 m along mid-section of the flume.

MATERIALS

The test samples are soft mud from the estuary of Kuala Selangor river and commercial grade kaolinite.

METHODOLOGY

Seven test beds were investigated to determine the rate of erosion as shown in Table 1. To demonstrate the effect of salinity on soft mud erosion, four test runs on Kuala Selangor mud with different salinity were conducted. Another three beds of kaolinite were tested to observe the effect of consolidation period.

TABLE 1. Seven test runs for the erosion studies

Sample	Run No.	Salinity (ppt)	Consolidation (days)
KS mud	1	1.0	1.75
	2	2.0	1.75
	3	5.0	1.75
	4	10.0	1.75
Kaolinite	5	10.0	1.75
	6	10.0	2.75
	7	10.0	5.75

Each test run was divided into one hour time step. The suspension concentration of fine sediment was measured for each 5, 15, 30, 45, and 60 minutes interval. Erosion rate was calculated according to the following equation:

$$\varepsilon = h\frac{dc}{dt}, \tag{1}$$

where ε = average erosion rate, measured in grams per square centimeter per minute,

h = depth of flow above the bed surface, which is a constant for the present study,

$\frac{dc}{dt}$ = rate of change of concentration calculated over 5, 15, 30, 45, and 60 minute interval.

In the present study, average erosion rate, ε, was used in determining the time dependent erosion rate. Erosion pattern was observed as each test bed was scoured layer by layer. Emphasis was given to evaluate a relationship between average erosion rate ε and excess bed shear stress $\left(\tau_b - \overline{\tau_s}\right)$, where ε = average of individual erosion rate for 5, 15, 30, 45, and 60 minute time intervals, and $\overline{\tau}_s$ = mean bed shear strength as a function of depth.

RESULTS AND DISCUSSION

TIME-VARIED RATE OF EROSION

The logarithm of average erosion rate, ε, for each time step was plotted against the time intervals and is shown in Figure 1. Similar plotting for all seven test beds are available in Rahman Mahbubur (1993) and all the plottings showed the same variation as in Figure 1. An exponential regression yields a straight line with a slope λ and an intercept ε_0 which has the following form:

$$\varepsilon = \varepsilon_0 \exp(-\lambda t). \tag{2}$$

The following observations were made from the above plottings:

1. Rate of erosion for the KS mud and kaolinite bed was found to decrease with time.
2. ε_0 is at an intercept at zero time, which can be expressed as an initial erosion rate. Despite the anomaly, the general trend was increasing initial erosion rate values with each time step. Therefore, with increasing bed shear stress value, the ε_0 value increases with each eroding layer.
3. There was no particular order variation of slope λ for each time step.

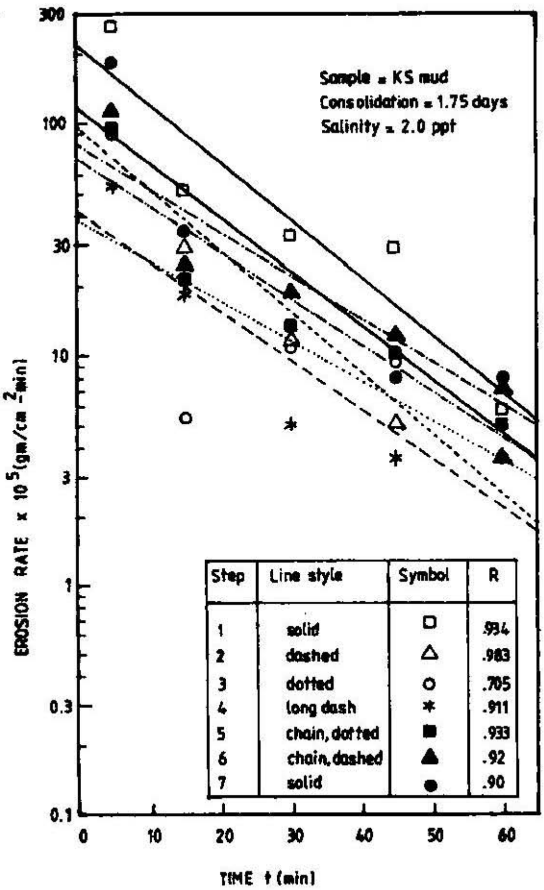

FIGURE 1. Erosion rate versus time for the second run

In Figure 2 and 3, the average erosion rate were plotted against the bed shear stress and the following observations were made:

1. Erosion rate for KS mud at 5.0 ppt salinity is higher than that at 10.0 ppt. With increasing salinity, interparticle bonds become stronger i.e. increasing in shear strength with depth. The principal mechanism has been described in double layer theory.
2. At lower applied bed shear stress, the average erosion rate for kaolinite was found to decrease with increasing consolidation period. While at higher bed shear stress, the variation is reversed. In between these two opposite changes, it appeared that the effect of consolidation is negligible at a particular depth. In the present study, this depth is termed as characteristic consolidation depth z_{dc}. Up to the characteristic consolidation depth, consolidation due to overburden and crushing increased and beyond this the consolidation due to overburden remained the same. As the flow-induced applied bed shear stress increases with each time step, the bed with uniform consolidation (below z_{dc}) is subjected to more erosion.

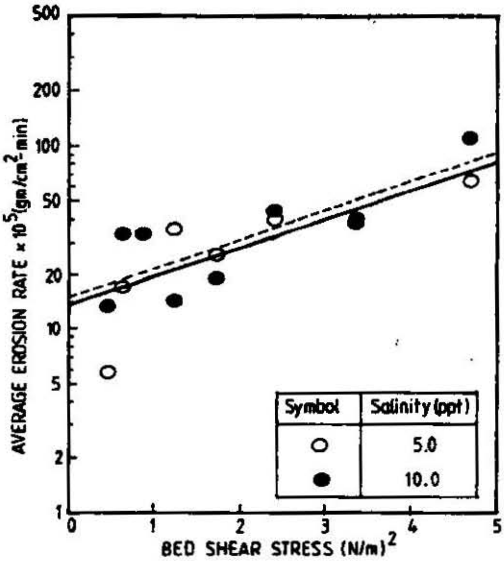

FIGURE 2. Effect of salinity on the average erosion for the KS mud

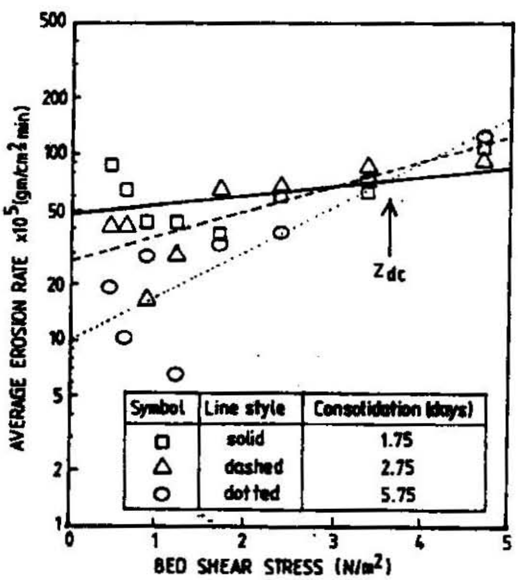

FIGURE 3. Effect of consolidation on the average erosion rate for the kaolinite bed

The slope and the interception of each line in Figure 3 are plotted against the consolidation period as shown in Figure 4 and 5 and the following observations were made:

1. The slope λ_1 increases with consolidation period. As the erosion rate decreases with higher consolidation, the increasing value of slope should be associated with the lower rate of erosion.

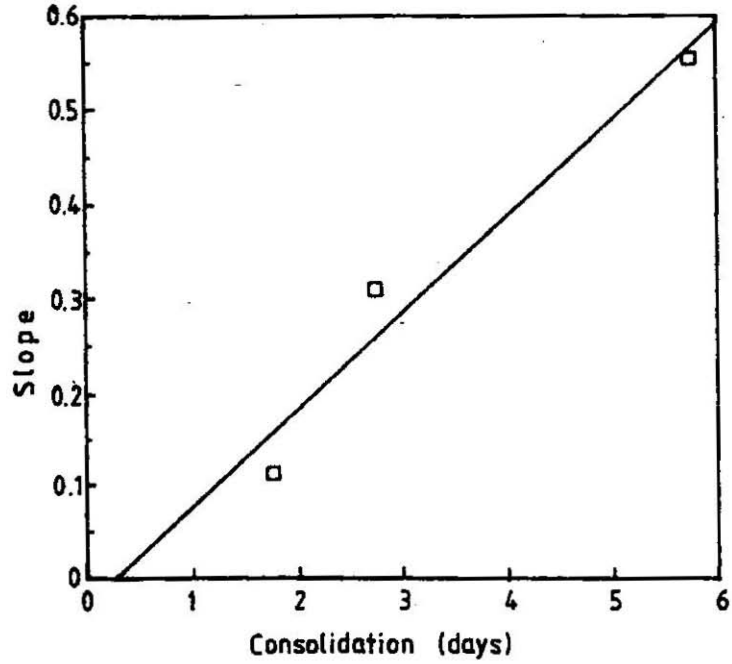

FIGURE 4. Consolidation period versus slope of the line

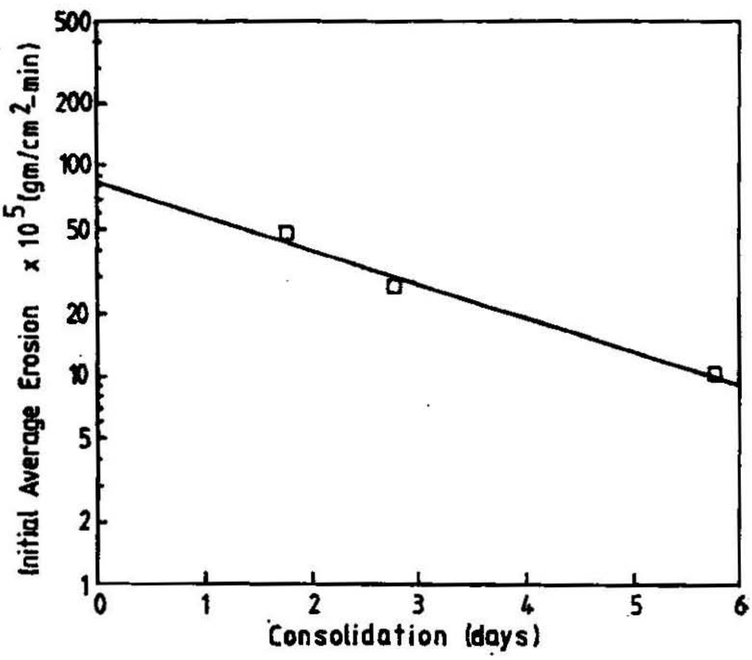

FIGURE 5. Consolidation period versus initial average erosion

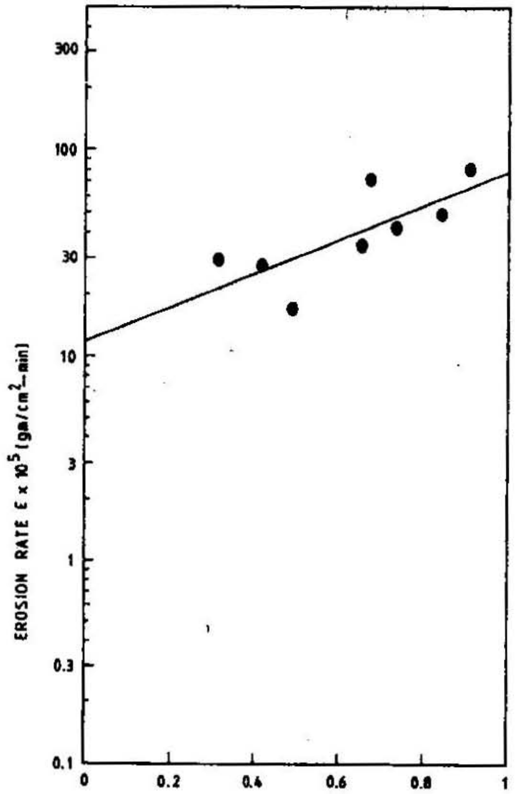

FIGURE 6. Rate of erosion for the first run

2. Initial average erosion rate decreases with increasing consolidation. The reason is due to the increasing compaction of soft soil network with consolidation.

EROSION RATE FOR PRESENT STUDY

To describle the erosion rate of soft mud, the Rate Process Theory has been used by many researchers such as Gularte (1978), Kelly & Gularte (1981) and Parchure (1984). According to the Rate Process Theory in describing erosion, the rate of erosion is varied exponentially with excess bed shear stress at constant temperature. It was assumed that the temperature was constant throughout the present investigation.

The analysis of the available data in the first run (KS mud, salinity 1.0 PPT, consolidation 1.75 days) indicated that the logarithm of average erosion rate varies with the cubic root of excess bed shear stress as shown in Figure 6. All the plottings for seven test beds showed the same variation and the relationships are shown in Table 2.

A general expression may be as follows:

$$\ln \varepsilon = \theta\left(\tau_b - \overline{\tau_s}\right)^{1/3} - \varepsilon_f, \qquad (10)$$

where,

θ = slope of the plotting,

ε_f = floc erosion rate.

TABLE 2. Relationship found for the seven test beds

Sample	Salinity (ppt)	Expression	Equation No.
KS mud	1.0	$\ln \varepsilon = 1.87 \left(\tau_b - \overline{\tau_s}\right)^{1/3} - 9.01$	(3)
	2.0	$\ln \varepsilon = 1.407 \left(\tau_b - \overline{\tau_s}\right)^{1/3} - 8.80$	(4)
	5.0	$\ln \varepsilon = 2.87 \left(\tau_b - \overline{\tau_s}\right)^{1/3} - 9.93$	(5)
	10.0	$\ln \varepsilon = 2.265 \left(\tau_b - \overline{\tau_s}\right)^{1/3} - 9.568$	(6)
	Consolidation	**Expression**	
Kaolinite	1.75	$\ln \varepsilon = 2.62 \left(\tau_b - \overline{\tau_s}\right)^{1/3} - 9.247$	(7)
	2.75	$\ln \varepsilon = 0.776 \left(\tau_b - \overline{\tau_s}\right)^{1/3} - 7.98$	(8)
	5.75	$\ln \varepsilon = 5.23 \left(\tau_b - \overline{\tau_s}\right)^{1/3} - 11.43$	(9)

where,
ε = average erosion rate, measured in gram per square centimeter per minute.
r_b = time-mean bed shear stress, expressed in newton per square meter
$\overline{\tau_s}$ = mean bed shear stress, calculated over each eroding layer

A non-dimensional combined plotting of $\ln\left(\frac{\varepsilon}{\varepsilon_f}\right)$ versus $\left(\tau_b - \overline{\tau_s}\right)^{1/3}$ yields the following expressions for each KS mud and kaolinite sample.

KS mud $$\ln\left(\frac{\varepsilon}{\varepsilon_f}\right) = 2.088 \left(\tau_b - \overline{\tau_s}\right)^{1/3}. \quad (11)$$

Kaolinite $$\ln\left(\frac{\varepsilon}{\varepsilon_f}\right) = 3.765 \left(\tau_b - \overline{\tau_s}\right)^{1/3} - 0.1. \quad (12)$$

After ignoring the intercept value in the equation for kaolinite, the following erosion rate expression was proposed for the present study:

$$\ln\left(\frac{\varepsilon}{\varepsilon_f}\right) = \theta\left(\tau_b - \overline{\tau_s}\right)^{1/3}. \quad (13)$$

The significance of the slope, θ, and the floc erosion rate, ε_f, and their comparison with those of previous studies were described in the following section.
The scattering of data points might be due to the following reasons:

1. Depth variation of shear strength, τ_s, was determined by subjecting each bed to a layer by layer erosion instead of using any instrument.

This may caused some deviation in shear strength from the actual value.
2. The applied bed shear stress was a time-mean average value. Therefore, the eroding pattern under average value might have been different from that of under instantaneous bed shear stress value.

SIGNIFICANCE OF ε_f AND θ

The values of ε_f and θ from the seven test run are as given in Table 3.

TABLE 3. Values of ε_f and θ for the seven test runs

Samples	Salinity (ppt)	T_{dc}	ε_f ($\times 10^{-5}$)	θ
KS mud	1.0	1.75	12.17	1.87
	2.0	1.75	15.02	1.41
	5.0	1.75	4.88	2.87
	10.0	1.75	6.99	2.26
Kaolinite	10.0	1.75	34.08	0.77
	10.0	2.75	9.64	2.62
	10.0	5.75	1.086	5.23

From Table 3, the following observations were made:

1. Although there is no particular order of variation in ε_f and θ values for different salinity, at higher salinity (5.0 and 10.0 ppt) the ε_f value is lower, while the θ is higher compared to those of lower salinity (1.0 and 2.0 ppt).
2. An increasing order of θ value associated with decreasing order of ε_f value was observed for kaolinite with increasing consolidation period. Usually a higher value of θ indicate a higher rate of erosion and/or a lower values of ε_f.

In Figure 7 and 8, the value of θ for kaolinite is higher than that of KS mud, which indicates a comparably higher erosion rate for kaolinite. These figures was based from equation (13). The reason is due to the less electrochemical surfacial forces on the kaolinitic clay particles. The mutual variation of floc erosion rate ε_f, and the slope θ is given in Figure 9, and the plotting indicates an inverse variation between these important two coefficients. The values of ε_f and θ obtained by previous researchers were as shown in Table 4.

In comparison with the previous values, the present investigation's values of θ and ε_f are lower and higher respectively. The reasons may be due to the differences in the following:

1. Test bed thickness.
2. The procedure adopted to determine the mean bed shear strength
3. Type of sediment.
4. Flume structure and near bed hydrodynamics pattern.

TABLE 4. Values of θ and ε_f from previous studies

Sample	Salinity (ppt)	T_{dc} (days)	ε_f ($\times 10^{-5}$)	θ	References
San Francisco Bay mud	33	7	0.04	8.3	Partheniades (1962)
Lake mud	*	-	0.42	8.3	Lee (1979)
Gragemouth mud	26	2	0.42	8.3	Thorn & Parsons (1977)
Belawan mud	32.7	2	1.85	4.2	Thorn & Parsons (1977)
Kaolinite	*	6	0.60	25.6	Dixit (1982)

* Tap water

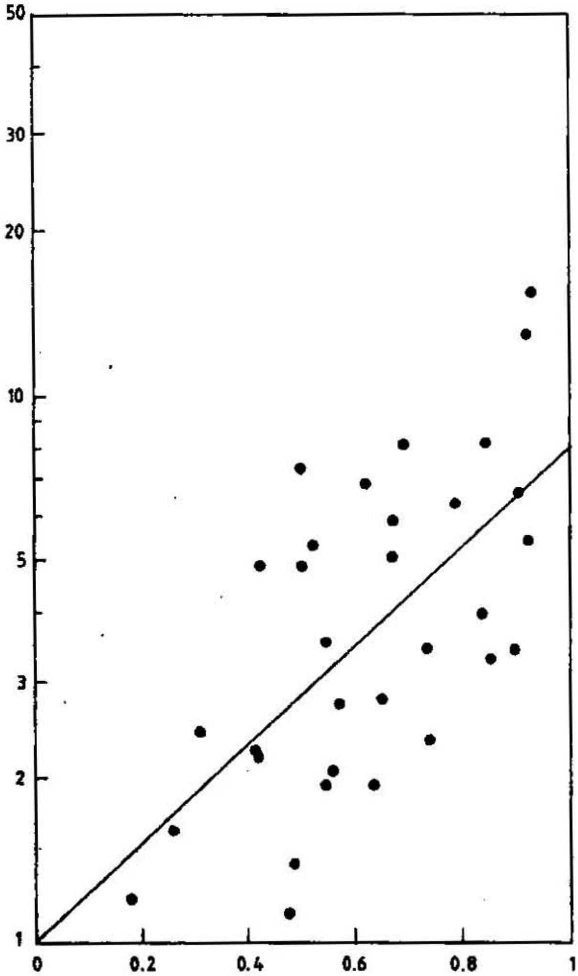

FIGURE 7. Non-dimensional plot erosion rates for KS mud

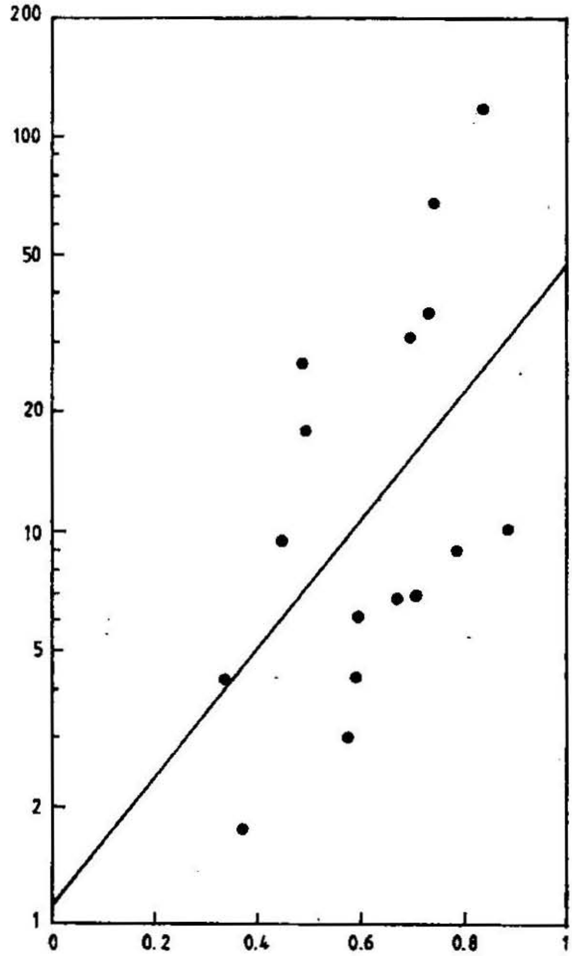

FIGURE 8. Non-dimensional plot of erosion rates for kaolinite

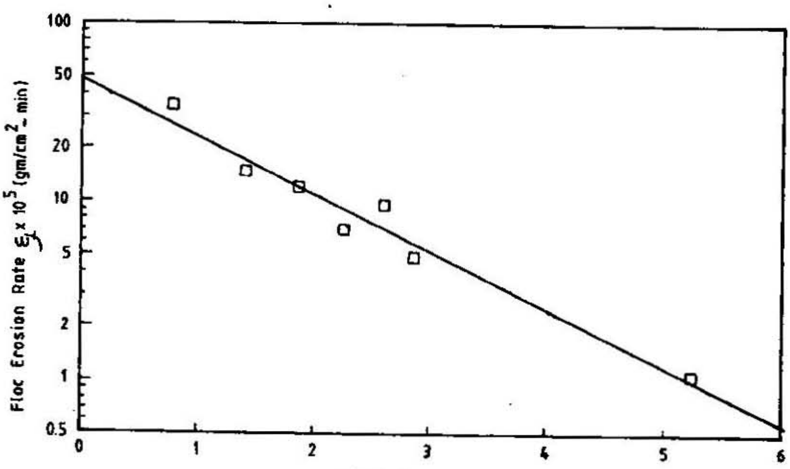

FIGURE 9. Relationship between the slope Q and the floc erosion rate

CONCLUSION

From the above discussions it can be concluded that the rate of erosion of fine cohesive sediment decreases with time. Depthwise appearance of stronger interparticle bonds and compaction due to salinity and consolidation caused a reduction in the rate of erosion with respect to depth. Below the water sediment interface, a characteristic consolidation depth Z_{dc} existed, beyond which, the change in bed structure due to consolidation is unlikely to happen, i.e. the bed is with uniform consolidation. Logarithm of average erosion rate was found to vary with cubic root of excess bed shear stress. The proposed rate expression (Equation 13) is recommended for the modelling of erosion in any specific site investigation. The value of parameters ε_f and θ usually depended on the type of sediment and the eroding fluid.

ACKNOWLEDGEMENT

Support provided by project IRPA: 4-07-03-017 and 4-07-03-037 are sincerely acknowledged.

NOTATIONS

ε = average erosion rate
ε_f = floc erosion rate
ε_0 = initial erosion rate
h = depth of flow
λ, λ_1 and θ = empirical coefficient
τ_b = bed shear stress
τ_s = shear strength
τ_s = consolidated period
T_{dc} = consolidation period
Z_{dc} = characteristic consolidation depth

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