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Erosion resistance of cohesive sediments in turbulent flow

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Abstract A series of experiments on erosion resistance of cohesive soil were conducted in a straight flume and in an annular rotating fibreglass channel-ring system (Cao & Fang, 1991). The research confirmed that erosion resistance of cohesive sediments was controlled strongly by the bed shear stress, the consolidation degree, the free pore ratio and the experimental flow volume of bed material for a specific engineering problem. Equations relating erosion rate to the bed shear stress or free pore ratio of bed are derived from the results of experiments. For practical needs, a simple relation between dry density of bed and critical boundary shear stress is recommended.

INTRODUCTION

Erosion of cohesive sediments is common in highways, railways, irrigation channels, navigation rivers and reservoirs. Erosion of cohesive river banks and migration of meandering cohesive channels have received attention in recent years. Forces acting on cohesive sediments are quite complex and relate not only to particle size but also to mineral composition and environment. The erosion behaviour of cohesive sediments in a turbulent flow field plays a dominant role in engineering problems.

Compared with noncohesive sediment, cohesive particles have a large specific surface area which is defined as the surface of the particles per unit weight. The specific surface area of quartz particles with a diameter of 1 mm is 0.0023 $m^2\ g^{-1}$, but the specific surface area of montmorillonite can be as large as 750 $m^2\ g^{-1}$. The latter is 3.26×10^5 times the former. Cohesive soil is mainly composed of kaolinite, illite and montmorillonite. The most cohesive particles are slices or needles, so the magnitude of electrochemical cohesive forces are several orders larger than the gravitational forces. The cohesive forces may be 10^5 times as large as the gravitational forces for cohesive particles with a diameter of 0.001 mm. The rate process theory may be useful for understanding the erosion resistance of cohesive soil. The similarity of erosion at constant stress to creep at constant stress was recognized and the methodology to determine experimental action energies E_a and flow volume V was developed by Kelly & Gularte (1981). In this study, the flow volumes were determined by least squares regression analyses of the data from each run. They are 0.427×10^{13} cm^3 and 0.158×10^{13} cm^3 for two types of bed respectively. The results show that the flow volumes of this study are close to those of other erosion cohesive experiments which were undertaken in straight flumes (Kelly & Gularte, 1981), but the flow volumes from cohesive soil erosion study are several orders of magnitude greater than those for soil creep.

LABORATORY EXPERIMENTS

The experiments on erosion of cohesive sediments were undertaken in an annular rotating fibreglass channel-ring system (Cao & Fang, 1991). Mud from the flood plain of the Yellow River at Huayuanqou was used in the tests. Its d_{50} is 0.0039 mm. The plastic limit of Huayuanqou mud is 24.76%, the liquid limit is 43.39% and the plastic index is 18.63%. The loose pore ratio is 0.81. The mineral composition given by infrared scanner for the portion of $d <$ 0.002 mm is: 60-70% of illite and gaolite, 30% of calcite and less than 10% of quartz. The sodium adsorption ratio, SAR, is 5.19.

Twelve runs of erosion resistance experiment used two kinds of consolidating bed with different pore ratio. One bed with a pore ratio of 0.739 and a dry density of 0.70 g mm^{-3} was formed by a mixer. Another with a dry density of 0.55 g cm^{-3} was formed by natural deposition in the annular channel in two months. The free pore ratios are -0.507 and -0.107 respectively. The shear strengths are 10.4 g cm^{-2} and 4.16 g cm^{-2} respectively, which were measured by a fall bore with a bore angler of 60° and a weight of 60 g. The shear strength was calculated by the equation, $\tau' = kQ/h^2$, where Q is the weight of fall bore in gram; h, in mm, is the depth of the bed where the apex of the bore reached; k is a constant of 0.3; and τ' is the shear strength in t m^{-2}. During erosion, turbid water samples were taken through sampling taps. The process of concentration increasing with time was recorded in this way. Concentrations under 10 kg m^{-3} were tested by an electro-optical turbidity meter and concentrations above 10 kg m^{-3} by gravimetric analysis.

EROSION RESISTANCE

Figure 1 gives a sample of sediment concentration c varying with time t for erosion experiments. The dry density of the bed is 0.556 g cm^{-3} and bed shear stresses are 28, 46 and 66 N m^{-2} respectively. After about two hours of erosion, the sediment concentrations increase linearly. When shear stress is less than 16.1 N m^{-2}, the concentrations remain constant. Those data are not shown in Fig. 1 because the data points of low shear stress are too compact to be shown clearly. In the first two hours, the concentrations increase rapidly since the erosion resistance of the bed surface on which the fresh deposition of the last run has occurred, is quite low. Stable surface erosion occurs after about two hours. The erosion rates, E, are constant in the experimental range ($c <$

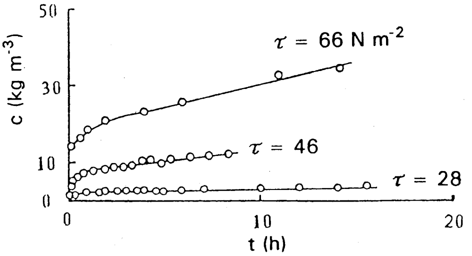

Fig. 1 Erosion processes.

35 kg m^{-3} and $\tau < 66.4$ N m^{-3}). The suspended sediments in the water column on a unit bed area can be represented as $E_0 = V_0c/A$, where the total volume of water in the annular channel $V_0 = 0.036$ m^3 and total bed surface area $A = 0.565$ m^2. E_0 is also the accumulative erosion amount on a unit bed area, in kg m^{-2}.

Figure 2 gives the relation of E and τ. When $\tau > \tau_c$, the equation is

$$E = (\tau/\tau_c - 1)$$

where τ_c is critical shear stress which can be determined by experiments. Erosion rate can also be expressed by the concentration gradient in volume ratio as $R = K(\tau/\tau_c - 1)/(\gamma_s h)$ where R is erosion rate in l h^{-1} and γ_s is the density of sediment in kg m^{-3}. Erosion coefficient K and critical bed shear stress are very complex and vary with the type of sediments, salinity, ionic species and amount, pH value and temperature of water. A preliminary correlation of K with free pore ratio e_r of bed is found in this study: e_r is a multiple index of sediments, which may reflect the effects of particle size distribution, the content of fine particles and the degree of consolidation. The free pore ratio is defined as $e_r = N_r/N_m$, where N_m is the actual pore rate of bed and N_r is the ratio of the difference between actual pore rate N_m and the loose pore rate N_s over the volume concentration in loose condition $N_r = (N_m - N_s)/(1 - N_s)$. N_s may reflect the effects of the particle size and the

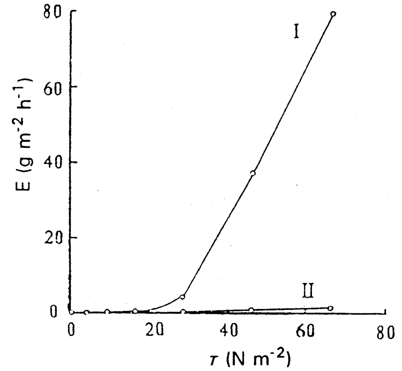

Fig. 2 E versus τ.

content of fine particles, which can be determined in laboratory as follows: put a certain amount of sediment with water in a marked vessel, mix well first, then let the sediment fall free, measuring the volume of deposited sediment at the end. The loose pore rate N_s can be calculated. The equation of e_r can be written in terms of the parameters N_s and N_m as $e_r = 1 - N_s(1 - N_m)/[N_m(1 - N_s)]$. The smaller the value of e_r, the lower the free degree of particles, the less the pore between particles, and therefore the larger the cohesion. Based on the data of the experiments, the relationship between K and e_r is given as $K = -13.9 - 133e_r$ where K is in g m^{-2} h^{-1}.

APPLICATION OF THE PROCESS THEORY

Some works have shown that the rate process theory may be useful for understanding the erosion resistance of cohesive soil. The similarity of erosion at constant stress to creep at constant stress was recognized and the methodology to determine experimental active energies E_a and flow volume V were developed by Kelly & Gularte (1981). Expressions of E_a (kcal mol^{-1}) and V (cm^3) can be written as:

$$E_a = \frac{RT_2T_1}{T_2 - T_1} \ln \left[\frac{E_2T_1}{E_1T_2} \right]$$

$$V = \frac{2kT}{(\tau_2 - \tau_1)} \ln \left[\frac{E_2}{E_1} \right]$$

where τ is the bed shear stress, E is the erosion rate, R is the universal gas constant (1.98 cal K^{-1} mol^{-1}), k is Boltzmann's constant (1.38×10^{-16} erg K^{-1} and T is absolute temperature. This study determined the flow volumes only by least squares regression analyses of the data from each run. They are 0.427×10^{-13} cm^3 and 0.158×10^{-13} cm^3 for the two types of bed respectively. Table 1 gives the comparison of this study with other authors. The results show that the flow volumes of this study are close to those of other erosion cohesive experiments

Table 1 Experimental flow volumes.

Material	Type of test	Flow volume (cm^3)	Reference
Huayuanqou mud	erosion	$0.158\text{-}0.427 \times 10^{13}$	This study
Illite (remodelled)	erosion - water tunnel	$0.154\text{-}6.09 \times 10^{13}$	Kelly & Gularte[a]
Illite	erosion - pipe	0.81×10^{13}	Christensen & Das[a]
Kaolinite	erosion - pipe	0.49×10^{13}	Christensen & Das[a]
San Francisco mud	erosion - flume	0.13×10^{13}	Partheniades[a]
Kaolinite	erosion - flume	0.13×10^{13}	Raudkivi *et al.*[a]
San Francisco mud	creep	8.7×10^{18}	Mitchell *et al.*[a]
Illite (remodelled)	creep	7.3×10^{18}	Mitchell *et al.*[a]
Illite (remodelled)	creep	3.0×10^{18}	Mitchell *et al.*[a]
Sault St Marie clay	creep	$0.6\text{-}4.2 \times 10^{18}$	Andersland *et al.*[a]

[a] Kelly & Gularte (1981).

which were undertaken on straight flumes (Kelly & Gularte, 1981), but the flow volumes from cohesive soil erosion studies are several orders of magnitude greater than those for soil creep. After the flow volume has been determined, the erosion rate can be calculated by the following equation:

$$E_2 = E_1 \exp\left[\frac{V(\tau_2 - \tau_1)}{2kT}\right]$$

DRY DENSITY VERSUS CRITICAL SHEAR

For engineering applications, erosion experiments with three kinds of soil were conducted in a straight flume with a length of 14 m, a bed slope of 0.05 and a width of 0.5 m. The soil samples to be tested were put in test boxes measuring 31 × 17 × 2.3 cm (length, width and depth) which were located in the centre of the flume. The surfaces of soil samples were the same level as the flume bed. The dry densities of soil samples, which were carefully prepared using a mixer, ranged from 0.64 to 0.98 g cm^{-3}. The characteristics of the soil samples are shown in Table 2.

Table 2 Soil characteristics.

Material	d_{50} (mm)	Initial dry density (g cm^{-3})	Fluid limit (%)	Plastic limit (%)	Plastic index (%)
Suicaozi mud	0.0058	0.64	51.95	30.00	21.95
HYQ mud	0.004	0.505	43.39	24.76	18.63
Beijing soil	0.023	0.56	30.90	19.70	11.20

During experiments, the discharge was increased step by step until the samples were deformed by fluid erosion. The samples of all runs were eroded as a type of structural deformation. For specific engineering problems, it is practical to develop a relation between dry density of cohesive sediment and the erosion critical bed shear stress. From the data of this study, the relation is:

$$\tau_0 = \alpha\gamma^{\beta}$$

in which α and β are constants. For this study, $\alpha \approx 0.7$ and $\beta \approx 5$ using the upper limit of the experimental data.

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