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Erodibility of Coarse Sand/ Clayey Silt Mixtures

by

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Erodibility of Coarse Sand/Clayey Silt Mixtures

INTRODUCTION

Natural soil systems are seldom composed entirely of cohesionless grains. However, in many instances, the natural soil may be composed mainly of sands and gravels with a relatively small percentage of fine material. Such is the case of the soils which occur on the Bucaramanga Plateau in Columbia, South America. The Bucamanga Plateau is subject to massive gully erosion. These gullies appear to be composed almost entirely of sands and gravels, but upon closer inspection, one finds several layers of very fine material through which the gullies have eroded. The question of stability of the gully beds can not then be answered based solely on the knowledge of the erodibility of sands and gravels.

Critical erosion conditions for natural soils have been the subject of several papers which are summarized in the recently published Sedimentation Engineering Manual (1975). However, these are largely cohesive soils which have a size range from silt to clay. Apparently little or no research has been done to investigate the erodibility of mixtures consisting of the coarser cohesionless size particles and fine material of the silt and clay size. Furthermore, the definition of parameters which are important for the erosion of cohesive sediments is very incomplete.

This report presents results of a laboratory study concerning the erosion characteristics of soil mixtures composed of a uniform coarse sand mixed with various percentages of a silty soil.

EXPERIMENTAL SETUP AND PROCEDURES

In order to investigate the erosion characteristics of coarse sand mixed with clayey silt, a series of flume tests was conducted. Various percentages by weight of clayey silt were mixed with a uniform coarse sand. The mixture was then placed in a flume and subjected to erosive action of water. Water flow rates, depths, and time rate of material eroded were measured.

The Flume. The flume was constructed of plexiglass, 152 cm long, 11 cm wide, and 11 cm deep. A headbox and a tailbox were attached to the flume as shown in Figure 1. The headbox was equipped with baffles to form a quiet uniformly distributed flow at the entrance to the flume. The tailbox was designed to serve as a sediment trap, with the water being removed via an overflow weir. The overflow weir was placed at the downstream end of the tailbox to ensure sufficient distance from the end of the flume to the weir for complete settling of the coarse sand particles. The fine silt particles, however, remained in suspension. The overflow weir consisted of a 9 cm diameter plastic pipe which was adjustable vertically.

Water from the tailbox discharged into a 300 liter reservoir from which a centrifugal pump recirculated the water to the headbox.

The Soil. The soil to be subjected to erosion was prepared by mixing various percentages by weight of clayey silt with a uniform coarse sand. The sand had a mean grain size of 0.80 mm and a uniformity coefficient of 1.40.

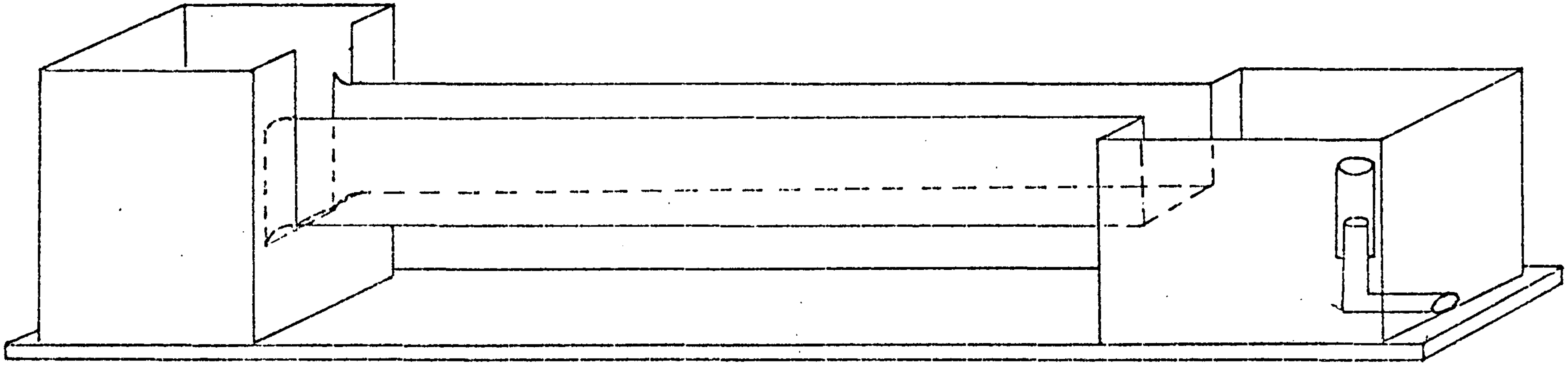

Fig. 1 - The Experimental Flume

The clayey silt consisted of approximately 85% silt, 10% clay (< 2 microns), and 5% fine sand (> 62 microns). A minerology performed on this soil revealed the clay fraction to be about 52% montmorillonite, 40% illite, and 8% kaolinite and chorite. The coarser silt fraction was found to be predominantly quartz. Standard tests for Atterburg limits determination yielded the following results: liquid limit = 33, plastic limit = 26, and plasticity index = 7.

The soil specimen was prepared by mixing the clayey silt with the sand in a moist condition. This ensured a uniform mixture of the clayey silt with the sand. The soil was then placed in the bottom of the flume to a depth of approximately 2 cm and a template was used to make the bed smooth. After placement of the soil in its moist state and smoothing with the template, the bed was allowed to air dry for 24 hours before testing commenced.

Measurement Procedures. At the start of a test, the soil bed was slowly flooded and at zero flow, bed elevations were determined from the horizontal water surface at four equally spaced stations over a 90 cm length of the flume. Discharge of water over the bed was then slowly increased until movement of the bed was observed. The discharge was then held constant for a period of 10 to 20 minutes during which time the water discharge was measured volumetrically, the sediment discharge was collected in the tailbox, and water depths were monitored at each of the four stations. At the end of the recorded time period, the water discharge was stopped and the eroded sediment removed from the tailbox. The water discharge rate was then increased and the same procedure repeated.

The average depth of flow during a series of runs was controlled by the tailbox overflow weir. A test series usually consisted of 4 different discharge rates during which the overflow weir remained at a constant level. Hence, during any given test series, the average water depths varied somewhat as a function of the discharge rate.

The flume was placed on a slope such that the flow was only mildly non-uniform over the range of flows for a given test series.

The sediment bed was observed closely during any given test series to ensure that excessive erosion, that would appreciably change the average bed elevation of the test section, did not occur. If such erosion did occur, the bed was removed and replaced according to the original procedure. Furthermore, after each test series, a sample of the bed material was analyzed to ensure that the percentage of clayey silt was the same as that during placement, since the collection of eroded sediment only included the coarser sand fraction.

RESULTS

Table 1 shows the ranges of variables encountered during testing. A total of 30 test runs were made.

Table 1 Range of Test Variables

Variable	Range
1. Average Velocity	26.-38. cm/sec
2. Average Depth	28.-38. mm
3. Sediment Transport Rate	10^{-6} - 10^{-3} kg/sec/m

Due to the small size of the flume and the subsequent difficulty in determining water surface slopes accurately, the bed shear stress was not calculated directly. Instead, for the initial data analysis, the sediment transport rate, g_s, was plotted vs. the average flow velocity, V, as shown in Figure 2. The lines drawn through the data points in this figure are simply best fit by eye. Next, the average velocity was used to determine bed shear stress by equation. The equation relating average velocity and shear velocity is given, according to Einstein (1950), as

$$\frac{V}{u_*} = 5.75 \log_{10}\left(12.27 \frac{R\,x}{k_s}\right) \tag{1}$$

where V is the average velocity, $u_* = \sqrt{\tau_o/\rho}$ is the shear velocity, τ_o is the bed shear stress, ρ is the fluid density, R is the hydraulic radius, k_s is the roughness of the bed, and x is a correction factor. The correction factor, x, is a function of k_s/δ, where δ is the thickness of the laminar sublayer for a smooth wall

$$\delta = \frac{11.6\,\nu}{u_*} \tag{2}$$

and ν is the kinematic viscosity of the flowing fluid. Since x is a function of u_*, the solution of equation (1) for τ_o as a function of V is a trial and error procedure. Fortunately for most of the range of variables tested in this study, the correction factor, x, is approximately constant and equal to about 1.5. Hence, equation 1 reduces to

$$\frac{V}{u_*} = 5.75 \log_{10}\left(18.4 \frac{R}{k_s}\right) \tag{3}$$

Furthermore, since the percentage of fine material in the bed was relatively small (18% maximum), the value of k_s was taken as constant and equal to the mean size of the uniform coarse sand. Then, since the

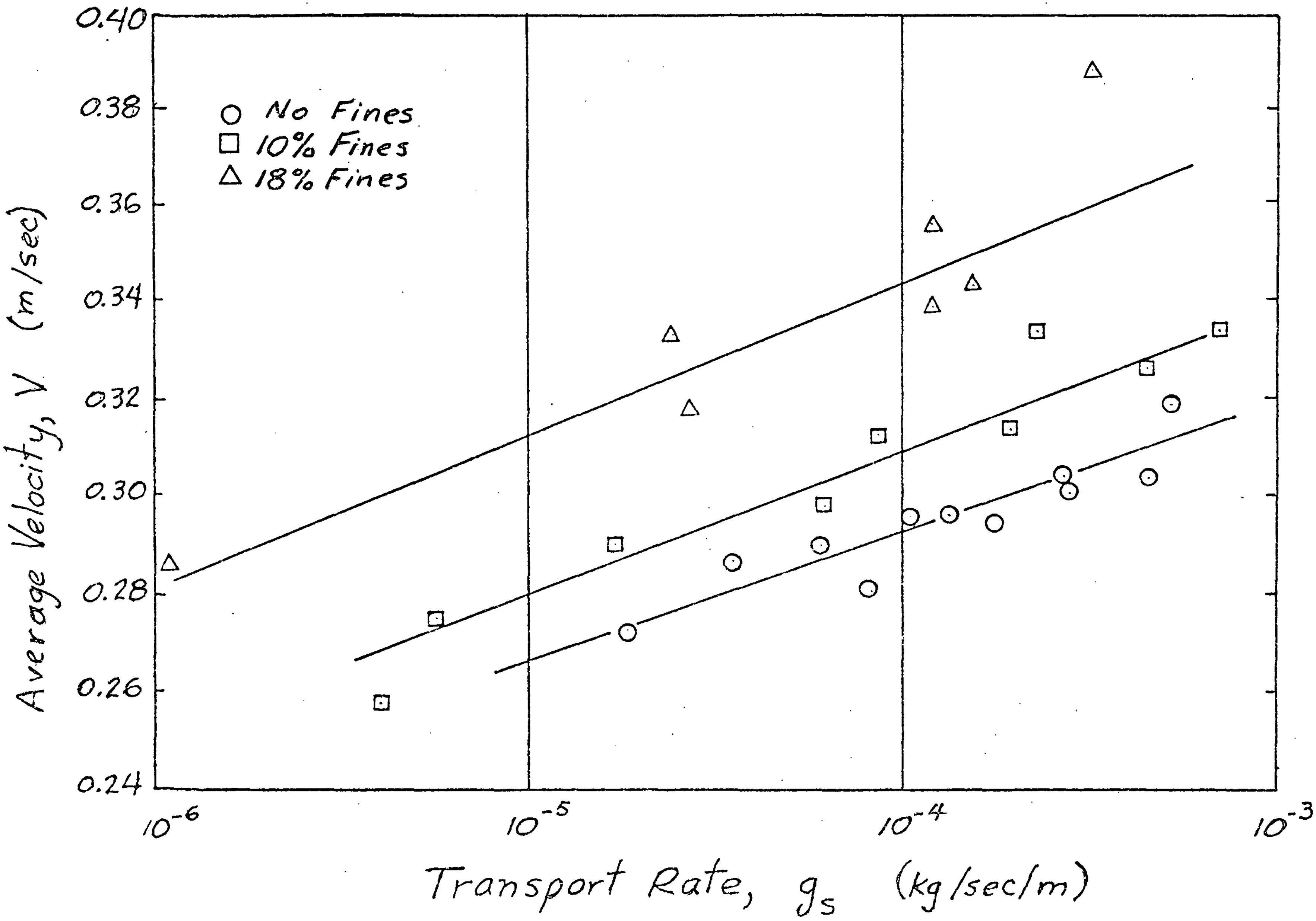

Fig. 2 - Erodibility as a Function of Average Velocity

range of hydraulic radius, R, over all tests was small, and furthermore this small variation occurs in the argument of a logarithm, the entire right hand side of equation (3) may be taken as constant. When this is done for the variables encountered during the experimental tests, the following equation is determined, relating average velocity, V, to bed shear stress, τ_o

$$\tau_o = \frac{\rho V^2}{190} = \frac{V^2}{98} \qquad (4)$$

Using equation (4), the data presented in Figure 3 are converted to a shear stress, τ_o, vs. sediment transport rate, g_s, plot, which is shown in Figure 3. The data points themselves are not transposed to the new plot, but only the straight lines which were fit to the data. It should be noted that the plot of average velocity, V, vs. sediment discharge rate, q_s, is a semi-log plot while the shear stress, τ_o, vs. sediment discharge rate, g_s, is a log-log plot. Therefore, one would not expect a straight line from Figure 2 to transform into a straight line on Figure 4 as shown. However, due to the very flat slope of the data, a tendency toward curvature of the transformed lines can not be detected.

Finally, in order to see the effect of varying the percentage of fine material more clearly, a plot of bed shear stress, τ_o, vs. percentage fine material, P_f, at various values of sediment discharge rate, g_s, is shown in Figure 4. Values for determining this variation were taken directly from Figure 3.

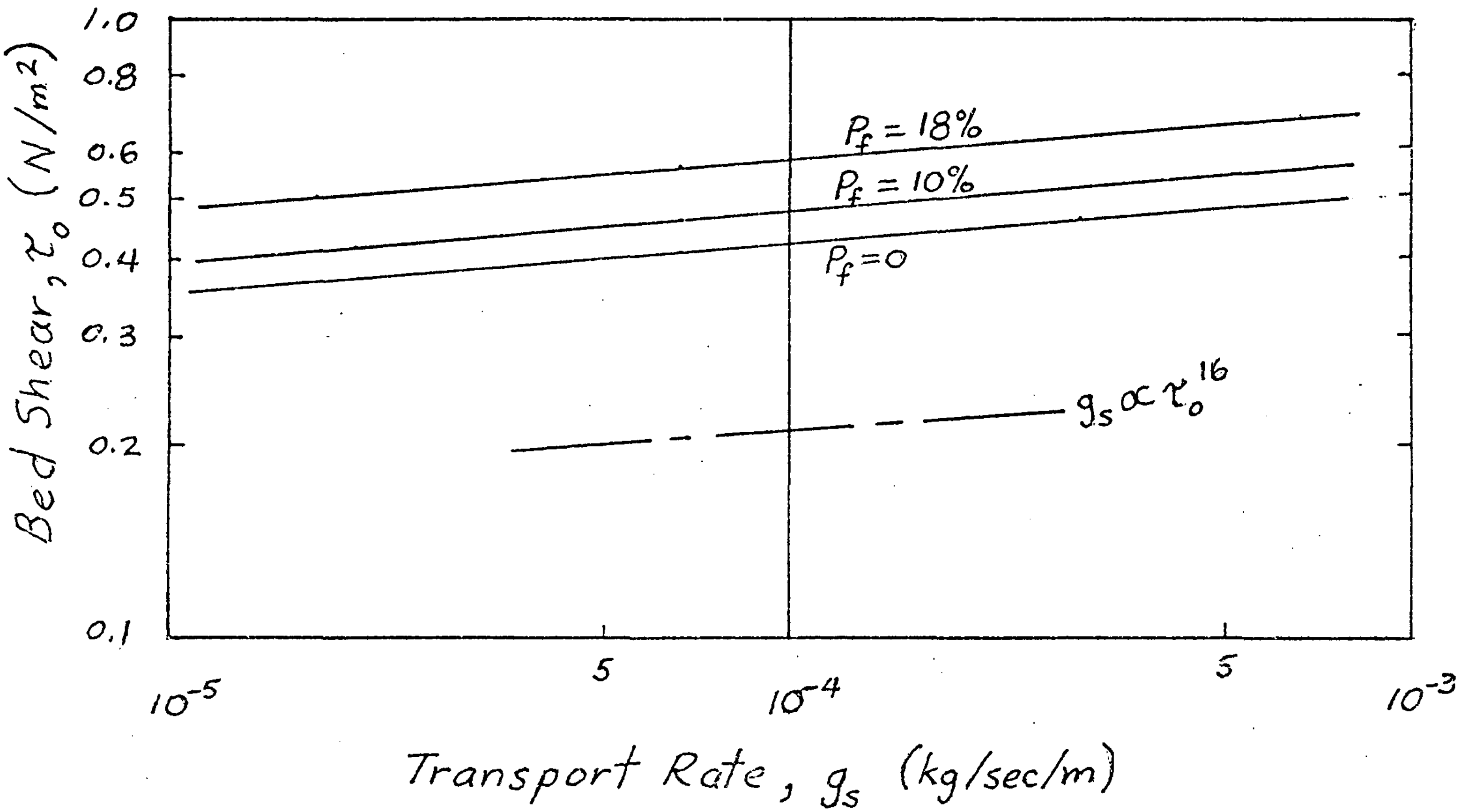

Fig. 3 - Erodibility as a Function of Bed Shear

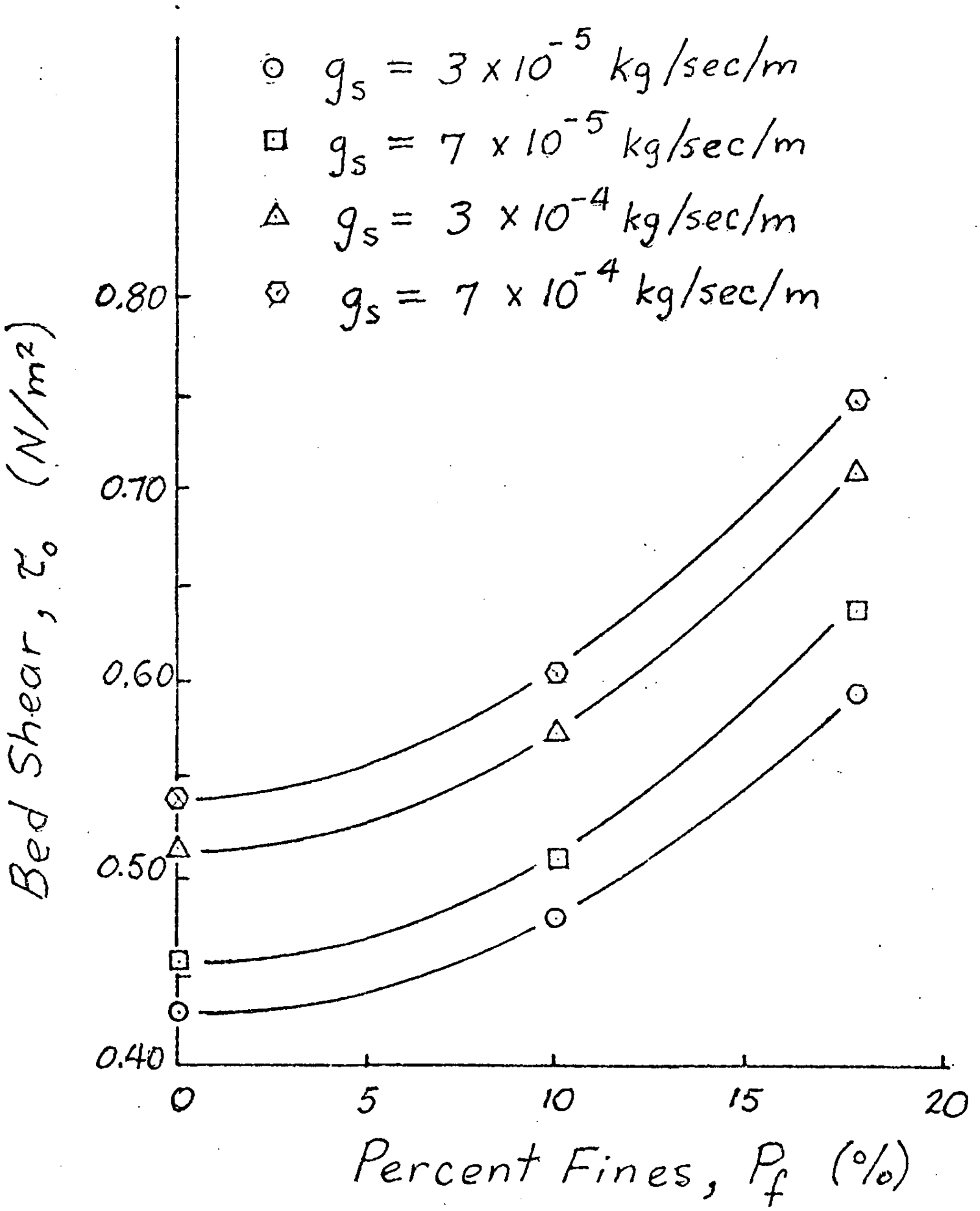

Fig. 4 - Variability of Transport Rate

DISCUSSION OF RESULTS

The results shown in Fig. 3 indicate a power law relationship between sediment transport rate, g_s, and bed shear stress, τ_o. This is precisely what has been found by Paintal (1971) for large cohesionless sediments. Paintal determined two distinct regimes of sediment transport; a low regime in which the transport rate is proportional to the 16th power of the bed shear stress, and a high regime in which the transport rate is proportional to the 2.5 power of the bed shear stress. Paintal has defined critical shear stress at the point where the transport rate changes from the low regime to the high regime. This transition point was found to occur at a dimensionless shear stress, τ_{o_*}, of 0.05 and at a dimensionless transport rate, g_{s_*}, of 10^{-2}, where

$$\tau_{o_*} = \frac{\tau_o}{(\gamma_s - \gamma)d} \tag{5}$$

$$g_{s_*} = \frac{g_s \, \rho^{1/2}}{d\gamma_s[(\gamma_s - \gamma)d]^{1/2}} \tag{6}$$

This definition of critical shear stress agrees well with accepted values.

For comparison with the data from this study, a line of $g_s \propto \tau_o^{16}$ is presented on Fig. 3. It can be seen that not only does the cohesionless sample follow the 16th power trend, but the bed samples with 10% and 18% fine material mixed with the coarse sand also follow the same power law trend. The value of the critical shear stress (as defined by Paintal, 1971) found in the present study for the coarse sand with no fines is lower than that found by Paintal, but this may be expected since the shear Reynolds number for this study is considerably lower than that experienced in Paintal's study (see Shields diagram).

Taylor (1971, as reported in ASCE Manual #54, 1975) found that at a constant value of dimensionless transport rate there exist a series of curves which parallel the Shields curve for dimensionless bed shear as a function of shear Reynolds number. The results shown in Fig. 3 would indicate that in addition to Taylor's findings, there may also be a series of parallel curves of the Shields type for various percentages of fine material mixed with predominantly coarser grains. However, the present data are too sparse to draw definite conclusions.

The fact that the bed shear stress required to move a given rate of sediment increases with the percentage of fine material in the sediment bed is to be expected, as has been shown by Dunn (1959), Smerdon and Beasley (1961), Grissinger (1966), and others as reported in ASCE Manual #54 (1975). However, most of these studies deal with natural soils whose overall grain sizes are quite small (usually silt sized and smaller). Little or no research has been done with mixtures such as used in this study.

The data in Fig. 4 show that the critical shear dtress does not increase as rapidly with percent fines as previously reported (Dunn, 1959; Smerdon and Beasley, 1961). This would suggest that the grain size distribution may also be a very important factor in determining the erodibility of a given soil.

In light of the present knowledge of the erodibility of cohesive soils, it seems that a more complete study of different sand grain sizes as well as different sand grain size distribution samples mixed with the same fine material sample may be fruitful. Furthermore, since Grissinger (1966) has found that the stability of cohesive materials varies with the amount and type of clay minerals in the soil, similar tests should be continued with different fine material samples.

CONCLUSIONS

From the experimental study results of the erodibility of coarse sand/clayey silt mixtures, the following conclusions may be drawn

1. The sediment transport rate for all sediment samples increased as the 16th power of the bed shear stress. This trend has been reported previously by Paintal (1971) for large cohesionless grains, but was found to be valid also for coarse sand mixed with small percentages of a clayey silt.
2. The bed shear stress necessary to transport a given rate of sediment increased as the percentage of fine material increased in the soil sample. However, the rate of increase with percent fines was less than previously reported.
3. It would appear that pursuing this type of experimental analysis will shed light on the overall problem of predicting the erodibility of cohesive soils.

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APPENDIX A

Flume Data

Erosion Data

Test #1

Sand only - d_{50} = 0.80 mm

Flow Conditions	Elevation - mm				Water Discharge		Temp.
	Sta. 1	Sta. 2	Sta. 3	Sta. 4	wt (lbs)	Time (sec)	°F
Sediment Surface	66	64	63	63			
Water Surface							
1 At zero flow	80	80	80	80			75
2 At Q_1	92	91.8	91.5	91	21	11.5	
3 At Q_2	93.8	93.5	93	92.2	21	10.0	
4 At Q_3	96.8	96	95.5	94.5	21	8.5	
5 At Q_4	98.5	97.5	97	96	21	7.5	

Sediment Collected	Weight (lbs)	Time (sec)
At Q_1	0.00595	600
At Q_2	0.0428	600
At Q_3	0.0846	300
At Q_4	0.1029	300

Note: Stations 1, 2, 3 and 4 are located at one foot intervals along the flume length.

Erosion Data

Test #2

Sand only - d_{50} = 0.80 mm

Flow Conditions	Elevation - mm				Water Discharge		Temp.
	Sta. 1	Sta. 2	Sta. 3	Sta. 4	wt (lbs)	Time (sec)	^{o}F
Sediment Surface	66	64	63	62			
Water Surface							
1 At zero flow	71	70	69	68			72
2 At Q_1	93	92	90.5	89	21	11.0	
3 At Q_2	96.5	94.5	93	91.5	21	9.5	
4 At Q_3	96	93.7	92.2	90.5	21	10.1	
5 At Q_4							

Sediment Collected	Weight (lbs)	Time (sec)
At Q_1	0.00683	360
At Q_2	0.0586	240
At Q_3	0.0454	300
At Q_4		

Erosion Data

Test #3

Sand only - d_{50} = 0.80 mm

Flow Conditions	Elevation - mm				Water Discharge		Temp.
	Sta. 1	Sta. 2	Sta. 3	Sta. 4	wt (lbs)	Time (sec)	°F
Sediment Surface	66	64	63	62			
Water Surface							
1 At zero flow	84.8	83.8	83	82			74
2 At Q_1	97.5	96	94.5	93.5	21	9.8	
3 At Q_2	95.5	94	92.5	91	21	10.8	
4 At Q_3	97.5	95	94	92.5	21	9.5	
5 At Q_4	98	96.5	95	93.5	21	8.8	

Sediment Collected	Weight (lbs)	Time (sec)
At Q_1	0.0322	720
At Q_2	0.0242	480
At Q_3	0.0397	420
At Q_4	0.0432	300

Erosion Data

Test #4

Sand (d_{50} = 0.80 mm) with 10% Silt

Flow Conditions	Elevation - mm				Water Discharge		Temp.
	Sta. 1	Sta. 2	Sta. 3	Sta. 4	wt (lbs)	Time (sec)	°F
Sediment Surface	66	64	62	61			
Water Surface							
1 At zero flow	74	73	72.5	71.5			76
2 At Q_1	97	95	94	92	21	9.9	
3 At Q_2	100	98	97	94.5	21	7.9	
4 At Q_3	102.5	100.5	99	96.5	21	7.3	
5 At Q_4	104	102	100.5	98/5	21	6.7	
6 At Q_5	99	97	95.5	93.5	21	8.4	

Sediment Collected	Weight (lbs)	Time (sec)
At Q_1	0.0253	300
At Q_2	0.0516	420
At Q_3	0.150	540
At Q_4	0.111	300
At Q_5	0.0275	600

Erosion Data

Test #5

Sand (d_{50} = 0.8 mm) with 10% Silt

Flow Conditions	Elevation - mm				Water Discharge		Temp.
	Sta. 1	Sta. 2	Sta. 3	Sta. 4	wt (lbs)	Time (sec)	°F
Sediment Surface	66	64	62	61			
Water Surface							
1 At zero flow	74	72	71	70			77
2 At Q_1	94	92	91	89	21	12.0	
3 At Q_2	96	94	92.5	91	21	10.5	
4 At Q_3	98	96.5	95	92.8	21	9.0	
5 At Q_4	101	98.5	97	95	21	8.0	

Sediment Collected	Weight (lbs)	Time (sec)
At Q_1	0.00154	720
At Q_2	0.00110	360
At Q_3	0.0121	360
At Q_4	0.0436	420

Erosion Data

Test #6

Sand (d_{50} = 0.80 mm) with 18% Silt

Flow Conditions	Elevation - mm				Water Discharge		Temp.
	Sta. 1	Sta. 2	Sta. 3	Sta. 4	wt (lbs)	Time (sec)	^{o}F
Sediment Surface	67	65.5	63.5	63.5			
Water Surface							
1 At zero flow	74	72	71	70			78
2 At Q_1	94.5	92.5	91.5	89	21	11.0	
3 At Q_2	96.5	94.5	93	90.5	21	9.5	
4 At Q_3	99	97	96	93	21	8.0	
5 At Q_4	101	98	97	95	21	7.5	

Sediment Collected	Weight (lbs)	Time (sec)
At Q_1	0.0025	600
At Q_2	0.00981	660
At Q_3	0.0581	900
At Q_4	0.0543	660

Erosion Data

Test #7

Sand (d_{50} = 0.80 mm) with 18% Silt

Flow Conditions	Elevation - mm				Water Discharge		Temp.
	Sta. 1	Sta. 2	Sta. 3	Sta. 4	wt (lbs)	Time (sec)	°F
Sediment Surface	66	64	63	62			
Water Surface							
1 At zero flow	73.5	72.5	71.5	71			76
2 At Q_1	99.5	97.5	96.5	94.5	21	8.1	
3 At Q_2	102	100	99	97	21	6.8	
4 At Q_3	103	101	100	98	21	6.1	
5 At Q_4	100	98	97	95	21	7.7	

Sediment Collected	Weight (lbs)	Time (sec)
At Q_1	0.0328	600
At Q_2	0.0383	600
At Q_3	0.0619	360
At Q_4	0.00793	600

APPENDIX B

Summary of Grain Size Analyses

A. Coarse Sand: Mechanical Analysis

$d_{10} = 0.60$ mm

$d_{35} = 0.74$ mm

$d_{50} = 0.80$ mm

$d_{65} = 0.85$ mm

$d_{90} = 0.92$ mm

B. Clayey Silt: Hydrometer Analysis

% finer	d (mm)
68	0.042
57	0.031
50	0.026
44	0.023
36	0.017
29	0.013
23	0.0090
18	0.0065
14	0.0044
11	0.0026
10	0.0016
8	0.0012
7	0.00096
6	0.00078
5	0.00062