International Conference "Water, Environment, Energy and Society" (WEES–2009)
New Delhi, 12–16 January 2009

Effect of Cohesion on Detachment of Clay-Sand-Gravel Mixtures

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ABSTRACT: The knowledge of detachment and transport of sediments by the stream flow is necessary for solving various problems like soil erosion in catchments, reservoir sedimentation, stable channel design, river bed degradation *etc.* The condition for initiation of motion and process of detachment and transport of sediments by stream flows in the form of bed load and suspended load for cohesionless uniform and nonuniform sediments are reasonably well understood. However the catchment surface and river bed material consists of mixture of cohesive as well as cohesionless material. Present study was therefore taken up to investigate the effect of presence of cohesive material such as clay on initiation of motion and process of transport by detachment of cohesionless sediments consisting of the sand-gravel mixtures. For this purpose the experiments were conducted in a 16 m long, 0.75 m wide and 0.5 m deep tilting laboratory channel. Bed materials consisting of mixture of cohesionless material sand and gravel each mixed in equal portion by weight with varying proportions of cohesive material *i.e.* clay were used. Experiments were conducted under changing grain shear stresses and the erosion rate was measured in the form of bed load transport rate and suspended load transport rate. Results on bed load transport only are reported herein. Critical shear stress corresponding to the condition of initiation of erosion is identified. Preliminary results from the analysis are presented herein. The detachment characteristics of the cohesive sediment with gravel size material have not been studied as yet.

INTRODUCTION

The knowledge of detachment and transport of sediments by the stream flow is necessary for solving various problems like soil erosion in catchments, reservoir sedimentation, stable channel design, river bed degradation *etc*. Also the effect of detachment and deposition of fine material like clay on the river bed can be adverse to the aquatic life. Soil erosion occurs at accelerated rate in catchment areas wherein land surface soil mostly consists of clay, sand, gravel mixtures. Thus erosion of loose beds of sand, gravel and other material like clay and weak rocks are problems of considerable importance in the field of hydraulic engineering. Such erosion can also be caused by flow concentration, local flow acceleration, secondary flow, vortices or high velocity jets.

The condition for initiation of motion and process of detachment and transport of sediments by stream flows in the form of bed load and suspended load for cohesionless uniform and nonuniform sediments are reasonably well understood (Garde and Ranga Raju, 2000). However the catchment surface and river bed material consists of mixture of cohesive as well as cohesionless material.

For cohesionless sediments the main resistance to erosion is provided by submerged weight of sediment but in cohesive beds the net attractive inter particle surface forces and electro-chemical forces control the resistance to erosion. The main mechanisms which cause sediment to be moved in flowing water are the velocity of flow and shear and normal stress resulting from flow turbulence (Garde and Ranga Raju, 2000). When the shear stress due to flow approaches the critical value, the cohesive sediment starts getting detached from the bed and flowing water becomes turbid. This stage is described as the incipient motion condition of cohesive sediment, which is characterized by the beginning of erosion. With further increase in shear stress the sediment is detached from the bed and is transported by the flow.

The present study was taken up to investigate the conditions of incipient motion and process of transport by detachment of clay-sand-gravel mixtures by the channel flow. The investigations are made through laboratory experimentation. The detachment process of cohesive sediments having gravel size sediment present in it has not been studied as yet.

BRIEF REVIEW

Earlier studies on the erosion of clay-silt-sand mixtures indicated that erosion resistance of sediment bed

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increases with increase in clay percentage in the bed material (Kamphuis and Hall, 1983; Hanson, 1990; Mitchener and Torfs, 1996; Hanson and Hunt, 2006). Robinson and Hanson (1995) studied the effect of compaction on the head cut erosion process on two types of soils. The head cut advance rate was found to decrease with an increase in average dry density and unconfined compressive strength of sediment bed. Panagiotopoulos *et al.* (1997) have presented experimental results on influence of clay on the threshold of movement of fine sandy beds under unidirectional and oscillatory flows. They concluded that critical bed shear stress required to displace fine grained sand is increased by the order of up to 90% with the addition of clay and sediment bulk density is reduced with the addition of clay under unidirectional flow. Dey and Westrich (2003) conducted experiments to study the temporal variation of scour depth and flow characteristics of the quasi equilibrium state of scour of a cohesive bed. Using the dimensional analysis they proposed an empirical equation for computing the time variation of maximum scour depth. Aberle *et al.* (2004) developed straight benthic in-situ flume to measure the erosion rate of cohesive sediments in fresh water and salt water environment. The erosion rate was found to be dependent on bulk density, water content, organic matter and sand content. Kothyari *et al.* (2006) have proposed a relationship to compute the critical shear stress of cohesive sediments as a function of plasticity index, antecedent moisture content, moisture content at saturation and void ratio by utilizing the data of Ansari (1999) and Laflan and Beasely (1960). However no studies are yet available on process of initiation of motion and detachment of cohesive sediments consisting of clay-sand-gravel mixtures. The present work has been taken up to fulfill this gap in the literature.

EXPERIMENTAL PROCEDURE

Flume

The experiments are being conducted in a tilting flume 16 m long, 0.75 m wide and 0.5 m deep located in the Hydraulic Engineering Laboratory of Civil Engineering Department, Indian Institute of Technology Roorkee. The channel has a test section of 6.0 m length, 0.75 m wide and 0.12 m depth starting at a distance of 8.0 m from channel entrance. Observations were made at various slopes of flume ranging from 2.417×10^{-3} to 8.0×10^{-3} are presented herein. The discharge in the flume was provided by a constant head overhead tank. The measurement of discharge is made volumetrically with the help of a tank provided at the end of the channel. The water supply into the flume was regulated with the help of a valve provided in the inlet pipe.

Material

Locally available clay excavated from a depth of 2.0 m below the ground was used as cohesive material. Tests for determination of clay properties were conducted as per Indian standard code (IS-1498, 1970). Laser particle size analyzer was used to obtain particle size distribution curve for clay. The clay material had a median size d_{50} equal to 0.0039 mm, geometric standard deviation σ_g equal to 1.5. Sand had a median size d_{50} of 0.23 mm and σ_g of 1.53, while gravel had a median size d_{50} of 3.1 mm and σ_g of 1.23. The relative density of sand and gravel was 2.65. Figure 1 shows the grain size distribution for clay, sand and gravel. The other engineering properties of clay material were: liquid limit W_L = 38%, plastic limit W_P = 24%, plasticity index PI = 14%, maximum dry density $(\gamma_d)_{max}$ = 18.27 KN/m^3, optimum moisture content OMC = 16%, cohesion at OMC, C_u = 54 KN/m^2 and angle of internal friction at OMC, $\Phi_c = 21°$ and relative density = 2.6. As per IS-1498, the clay was classified as *CI i.e.* clay with intermediate compressibility.

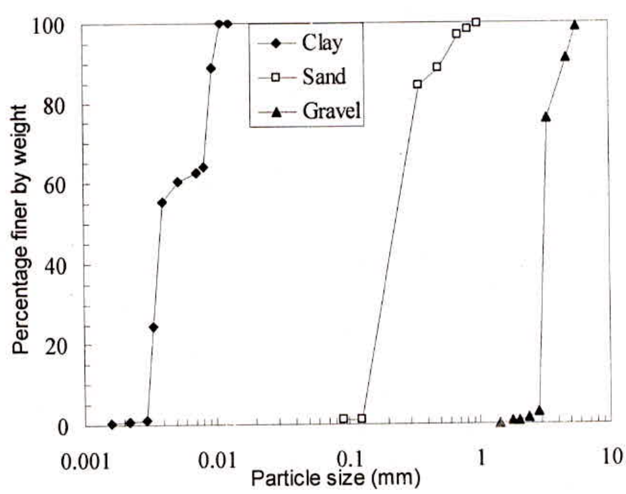

Fig. 1: Grain size distribution for clay, sand and gravel

Preparation of Bed

Accurately weighed clay powder, sand, gravel and already computed moisture (water) were mixed thoroughly. The mixed sediments were covered with polythene and left for 24 hours for uniform distribution of the moisture. The sediment was mixed thoroughly again before placing it into the test section. Thus prepared cohesive sediments were filled in the test section and compacted either by a dynamic compaction method or a kneading method depending upon the antecedent moisture content. The dynamic compaction method was adopted for cohesive sediments of hard, semi-solid and plastic consistencies. In dynamic compaction method the sediment was compacted in test section in three different layers each having thickness of 0.04 m. Each layer was compacted with a cylindrical roller of dimension 0.23 m diameter and 0.63 m length specially fabricated to fit into channel width. The dead weight of roller was equal to 100 N. Depending upon the required amount of compaction, the arrangement was also made to increase the compaction weight up to 200 N by filling water inside the roller body.

The kneading method of compaction was used for sediments of soft consistencies. Such sediments were dropped from a suitable height into test section in the form of small lumps and later sediments were compacted by a wooden rammer having flat base to ensure the uniformity of compaction throughout the test section. Prior to experimentation the prepared bed was saturated for 24 hours. The value of dry density and antecedent moisture content reported in the paper are measured at the completion stage of compaction or kneading.

Experimental Procedure

Desired discharge was allowed into the channel through the inlet pipe. Flow parameters corresponding to the condition of incipient motion in the sediment bed were determined. Bed load portion of the detached material was measured by collecting the sediment in a trap at the end of the flume. The water surface elevations were observed by pointer gauge having least count of 0.01 mm while bed elevations were measured by a flat bottom gauge. For each run the bed elevations and water surface elevations were measured at a longitudinal interval of 0.5 m along the centre line of the flume.

In all, 30 experimental runs were conducted on critical shear stress of cohesive sediment mixtures are reported here. Whereas 35 experimental runs were taken on transport by detachment of sediment mixtures are reported here. Out of which 7 runs were taken for transport by detachment of cohesionless sediment consisting of mixture of gravel and sand, while 28 runs were taken for transport of cohesive sediments consisting of clay-sand-gravel mixtures. In all 52 observations were taken for cohesionless sediment whereas 199 observations were taken for cohesive sediments. Range of sediment and hydraulic parameter collected for critical shear stress is provided in Table 1. Table 2 gives the range of sediment and hydraulic parameters collected on transport by detachment of cohesive sedíment mixtures consisting of clay-sand-gravel.

Here P_c in initial clay percentage in sediment bed, d_a is arithmetic size of cohesive sediment, w is antecedent moisture content, γ_d is dry density of sediment bed, h is flow depth, U is mean velocity of flow, S_f is energy slope, and τ_{*cc} is dimensionless critical shear stress of cohesive sediments.

Here τ is grain shear stress, q_{bg} is transport rate of gravel by detachment, q_{bs} is transport rate of sand by detachment.

Table 1: Range of Sediment and Hydraulic Parameters Collected for Critical Shear Stress of Cohesive Sediments

P_c (%)	d_a (mm)	w (%)	γ_d (KN/m^2)	H (m)	U (m/s)	S_f (–)	τ_{*cc} (–)
10	1.498	7.2–13.40	17.40–20.80	0.0251–0.0936	0.363–0.55	0.002–0.0058	0.041–0.059
20	1.332	7.2–15.2	17.62–19.25	0.0257–0.0852	0.428–0.562	0.0017–0.0058	0.051–0.081
30	1.166	7.42–21.69	16.27–19.01	0.0251–0.0875	0.45–0.57	0.0021–0.008	0.055–0.094

Table 2: Range of Sediment and Hydraulic Parameters Collected Transport by Detachment of Cohesive Sediments

P_c (%)	d_a (mm)	W (%)	γ_d (KN/m^2)	h (m)	U (m/s)	S_f (–)	τ' (N/m^2)	q_{bg} (N/m^2-s)	q_{bs} (N/m^2-s)
10	1.498	7.20–13.40	18.20–20.8	0.084–0.171	0.51–0.761	0.0014–0.0057	1.23–2.67	0.002–0.0501	0.0004–0.011
20	1.332	7.20–14.7	17.68–19.38	0.087–0.179	0.55–1.01	0.0013–0.0061	1.48–4.52	0.0011–0.0635	0.0001–0.0105
30	1.166	7.42–21.69	16.27–19.01	0.07–0.17	0.539–1.056	0.001–0.0085	1.35–4.65	0.001–0.046	0.0001–0.0077

ANALYSIS OF DATA AND DISCUSSION OF RESULTS

Critical Shear Stress

The process of initiation of motion cohesive sediment mixtures containing gravel is noticed to be significantly different than that of cohesionless sediments. At the lower percentage of clay in bed material (up to 20%) the detachment generally initiates in the form of individual particles detached from bed. At the higher percentages of clay (30%) in bed material, the detachment begins by removing thin flakes from sediment surface and that removal continues and lines are found to appear over the bed surface and this condition was identified as condition of incipient motion for such cohesive sediments. Figure 2 shows a typical bed surface at the condition of incipient motion.

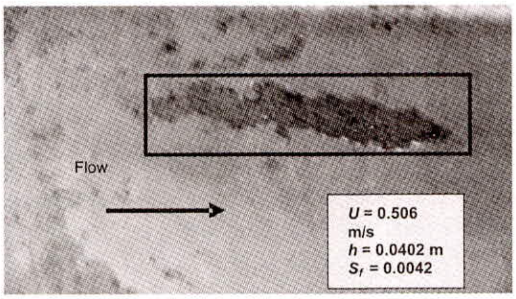

Fig. 2: Bed surface at the condition of incipient motion

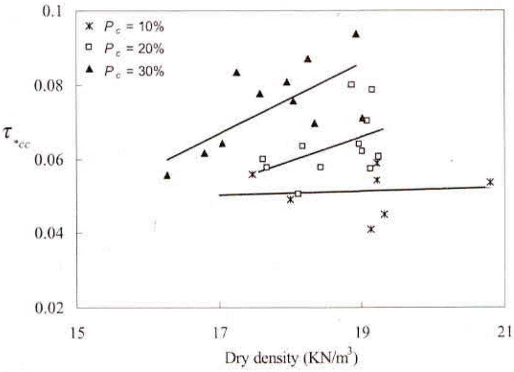

Fig. 3: Variation of τ_{*cc} with dry density and clay percentage

In order to identify the effect of compaction on critical shear stress of cohesive sediment, the variation of dry density with critical shear stress is studied. Figure 3 shows the variation of τ_{*cc} with dry density for 10% clay, 20% clay and 30% clay in bed material which indicates that τ_{*cc} increases with an increase in dry density of cohesive sediment bed. Figure 3 also reveals that τ_{*cc} increases with an increase of clay percentage in the bed material. Cohesion is significantly imparted to the sediment mixtures when the clay percentage is at or above 20% in the bed material therefore, the cohesive sediment with lower percentage of clay i.e. P_c = 10% is not following the similar trend which is also depicted by Figure 3.

Detachment of Cohesive Sediments

The transport cohesive sediments as bed load caused by detachment were observed to be considerably different from that of cohesionless sediments. While a lower percentage of clay (up to 20%) was present in bed material, the sediment mostly moved by rolling of the particles. However for higher clay percentages (30%) sediment particles were detached in the form of thick flakes from the bed surface leaving longitudinal lines which became considerably apparent on the bed surface and by the end of the run as depicted in Figure 4. Using the computed friction slope from observed water surface profile at different time intervals when the measurements of bed surface profiles and water surface profiles were made, the grain shear stress was computed which corresponded to the consequently measured average detachment and hence the transport rate.

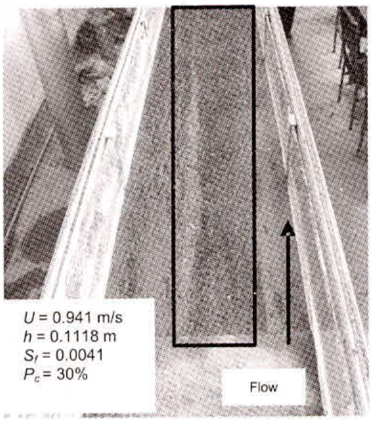

Fig. 4: Detachment pattern in cohesive sediment consisting of clay-sand-gravel mixture

In order to identify the influence of cohesion on transport of cohesive sediments by detachment, the value of erosion coefficient (s^{-1}) was determined as per Shaikh *et al.* (1988). The plots between grain shear stress and transport rate by detachment for cohesive sediments consisting of clay-sand-gravel are shown in Figures 5 and 6. The transport rate by detachment of cohesionless sediment present in the cohesive mixture is also shown in Figures 5 and 6. The value of erosion coefficient is determined as 0.0932 s^{-1} for cohesionless sediment (gravel) while its value is 0.0375 s^{-1} for 10% clay in bed material, 0.0175 s^{-1} for 20% clay in bed material and 0.0133 s^{-1} for 30% clay in the bed material. From Figure 6 the value of erosion coefficient is determined as 0.0231 s^{-1} for cohesionless sediment (sand) while its value is 0.0091 s^{-1} for 10% clay in bed material, 0.0027 s^{-1} for 20% clay in bed material and 0.0017 s^{-1} for 30% clay in the bed material. This clearly indicates that detachment rate of gravel and sand reduces drastically with an increase in the presence of clay fraction in it, which also means that rate of detachment of clay-sand-gravel mixture reduces with the increase of clay percentage in the bed material.

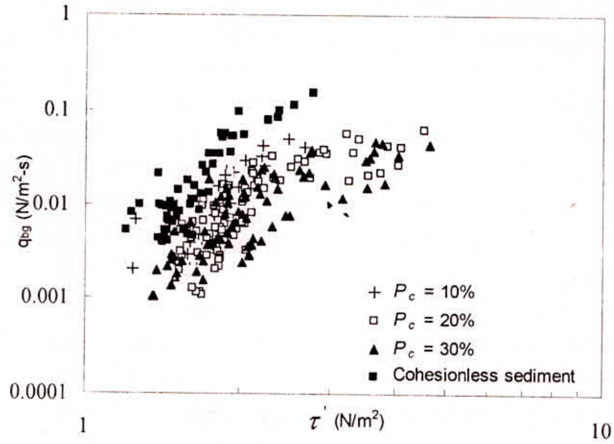

Fig. 5: Variation of detachment rate of gravel with grain shear stress

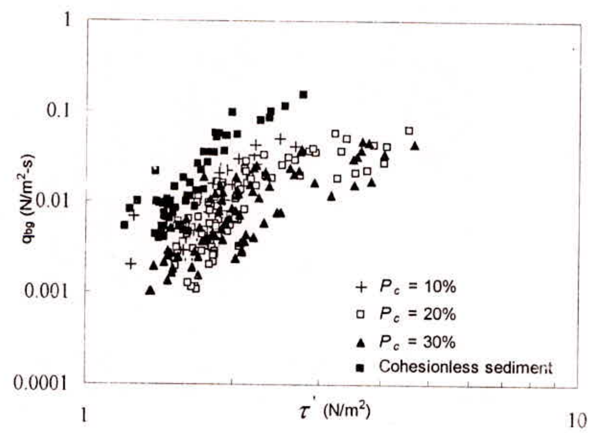

Fig. 6: Variation of detachment rate of sand with grain shear stress

CONCLUSIONS

On the basis of analysis of data collected on initiation of motion and transport by detachment of clay-sand-gravel mixtures, the following conclusions are drawn.

1. The process of initiation of motion and transport by detachment of cohesive sediments were observed to be considerably different from that of cohesionless sediment.
2. The dimensionless critical shear stress increases with an increase in clay percentage and dry density of the bed material.
3. The detachment rate of gravel and sand reduces drastically with an increase in the clay fraction in it. Also rate of detachment of clay-sand-gravel mixture reduces with the increase of clay percentage in the bed material.
4. The process of detachment of cohesive sediment having gravel size fraction present in it has been studied for the first time through the present study.

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