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Erosion characteristics of cohesive sediment mixtures

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ABSTRACT: The sediment particles having size smaller than 0.06 mm normally behave as cohesive material. When sand and gravel are mixed with clay and silt, the mixture also exhibits certain amount of cohesion. The erosion characteristics of such cohesive sediment mixtures are presented in this paper. The process of incipient motion condition, bed load transport and suspended load transport of cohesive sediment mixtures were observed to be significantly different from those of cohesionless sediments due to complex and interactive behavior of such sediment mixtures. Clay percentage and unconfined compressive strength of sediment bed are identified as the main parameters affecting the critical shear stress and transport of cohesive sediment. The topic on erosion of cohesive sediment mixtures containing clay and gravel was however not investigated in detail before.

Keywords: Cohesive sediment, Erosion, Transport, Clay percentage

1 INTRODUCTION

Knowledge on erosion behavior of cohesive sediments is necessary for solving various problems like soil erosion in catchments, reservoir sedimentation, river morphological predictions etc (Jain and Kothyari, 2009). Ecological investigations also require this knowledge as cohesive sediments affect the heath of aquatic ecosystem by degrading water clarity and transporting pollutants (Aberle *et al.*, 2006). Information on erosion characteristics of the cohesive sediment mixtures is also useful for mitigating the problem of soil surface erosion which may cause damage to the earth dams and highway embankments. Engineering project investigations for stream bank erosion and stability, scouring around hydraulic structures *etc.* would also benefit from such information (Jain and Kothyari, 2010). The sediments like clay normally behave as cohesive material. When sand and gravel are mixed with clay and silt, the mixture also exhibits certain amount of cohesion. In nature, the land surface specially in head water catchment and river bed and bank material frequently consist of the mixture of cohesive as well as cohesionless sediments like mixtures of sand, gravel and clay (Kothyari and Jain, 2008). Figure 1 depicts a view for example, showing presence of clay, sand as well as gravel on the bank of the river Ganga at Rishikesh in Himalayan Shiwaliks, India. Similarly Fig. 2 depicts view of the bed material composition of the river Ganga at Rishikesh, India which vividly confirms the presence of clay in the bed material along with sand, gravel and other materials. In the catchment areas of such rivers, removal of soils takes place from land surface by the action of rainfall and overland flow resulting into rill erosion and gully erosion.

The condition of incipient motion and bed load and suspended load transport of cohesive sediments and their mixtures are affected by large number of interdependent variable. The characteristics of constituent sediments also play an important role in such processes along with the flow and fluid characteristics as in the case of cohesionless sediments. For the given conditions of these variables the transport rate of cohesive sediments also varies with time (Jain, 2008). The topic of erosion behavior of cohesive sediments in the presence of clay and gravel is reviewed herein. Some additional data on this aspect is also presented.

Figure 1. River Ganga at Rishikesh, India

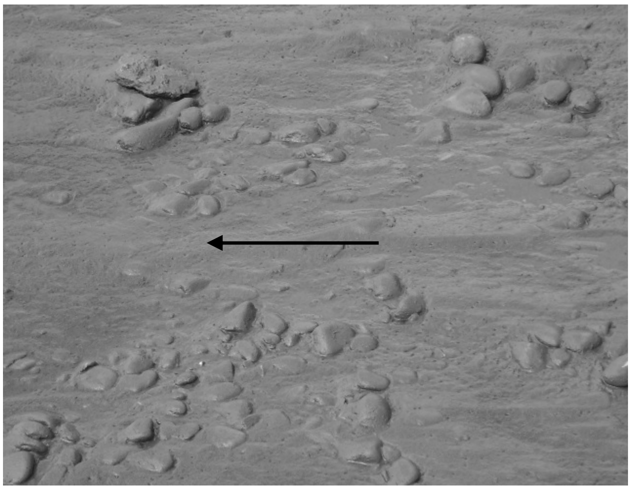

Figure 2. Bed material of river Ganga at Rishikesh, India

2 COHESIVE SEDIMENTS

The sediment particles having size smaller than 0.06 mm normally behave as cohesive material. However the cohesive sediment particles principally consist of clay minerals. The crystalline minerals of which surface activity is such that they develop cohesion and plasticity are called clay minerals. These clay minerals are mostly silicates of aluminum and/or iron and magnesium. There are two fundamental building blocks for crystalline clay mineral structures, one is silica tetrahedral unit in which four oxygen atoms having the configuration of a tetrahedron enclose a silicon atom, producing a unit approximately 4.6 A^0 high (Angstrom unit $A^0 = 10^{-10}$m), the second building block is an octahedral unit in which an aluminum, iron or magnesium atom is enclosed in six hydroxyls having the configuration of an octahedron which is about 5.05 A^0 high (Bowles, 1984).

The tetrahedral are combined in a sheet structure in such a manner that oxygen of the bases of all the tetrahedral are in a common plane. The octahedral units are put together into a sheet structure in which each hydroxyl is shared by two units. Some of the most common clay minerals are kaolinite, illite and montmorillonite. Relative percentages of these minerals present in clay affect its behavior. As a result, presences of these minerals also affect the interactive behavior of clay with sand and gravel (Roberts *et al.*, 1998). Montmorillonite is responsible for swelling and shrinkage characteristics of cohesive sediment. The data from experiments conducted by the authors on Illite clay are presented herein. In these experiments the percentage composition of various clay minerals as per Klages and Hopper (1985) was Kaolinite = 17.6%, Illite = 60.3%, Vermiculite = 15.3% and Chlorite = 6.8%.

2.1 Engineering Characteristics of Cohesive Sediments

Cohesive sediment dynamics is important for several engineering and ecological applications but its general theory is still unavailable (Black *et al.*, 2002). The cohesive sediments are composed of small particles having large specific area *i.e.* area per unit volume of particles. Due to this, the surface physico-chemical forces become much more important as compared to the particle weight. The physico-chemical forces include the attractive Van der waals forces and other bonding forces such as hydrogen bond, cat-ion bond, chemical cementation between particles by various compounds, the double layer and particle interaction forces *etc.* in the clay-water medium. These forces are not yet fully understood as these vary with degree of saturation, type of shear application, drainage condition, clay percentage, and type of clay *etc.* (Ansari *et al.*, 2003). Therefore the resistance of cohesive sediment to the shearing action of the stream flow is yet to be quantified. This resistance of cohesive sediment against erosion is primarily the function of different states of the internal structure of clay deposits and that varies from loose honey-combed state to dense state (Partheniades, 1965). The freshly deposited clay bed has a highly honey-combed structure with large void ratio. On the application of consolidation or compaction, the void ratio reduces and clay reaches to denser state having higher resistance to erosion.

2.2 Clay-Gravel and Clay-Sand-Gravel Mixtures

Jain and Kothyari (2009 & 2010) conducted laboratory experiments by preparing cohesive sediment mixtures by mixing clay material with fine gravel and with fine sand-fine gravel mixtures (each in equal proportion by weight) in proportion varying from 10% to 50% by weight. The amount of moisture content antecedently present in cohesive sediment has great influence on its physical properties (Ansari *et al.* 2002). Depending upon the moisture content present, the cohesive sediments change their stages *i.e.* liquid, plastic and non-plastic (semi-solid) as shown in Fig. 3. The tests were conducted under maximum possible range of antecedent moisture content so as to represent their different stages as anticipated in field conditions. The cohesive sediments were tested at various moisture consistencies ranging from very soft soil with negligible cohesion (viscous state) to hard soil with a high value of cohesion. Maximum dry densities and optimum moisture contents as obtained using the standard Proctor compaction test for various clay-gravel mixtures and clay-sand-gravel mixtures used in present study are given in Fig. 4. It may be noted from Fig. 4 that maximum value of dry density was attained in cohesive sediment mixtures while the clay percentage in the mixture varied from 20% to 30% by weight.

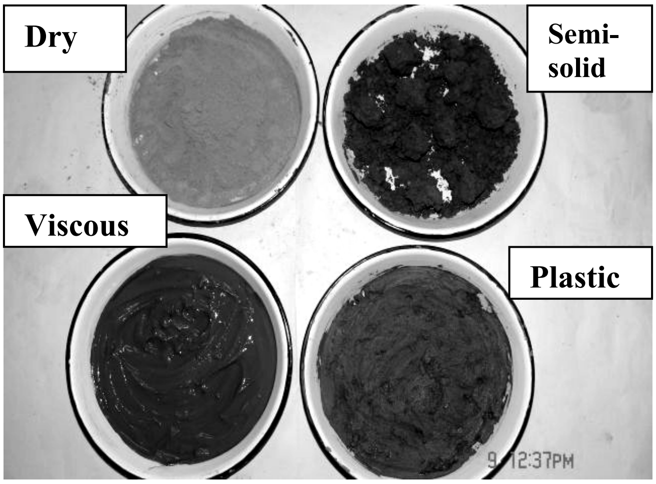

Figure 3. Various stages of clay

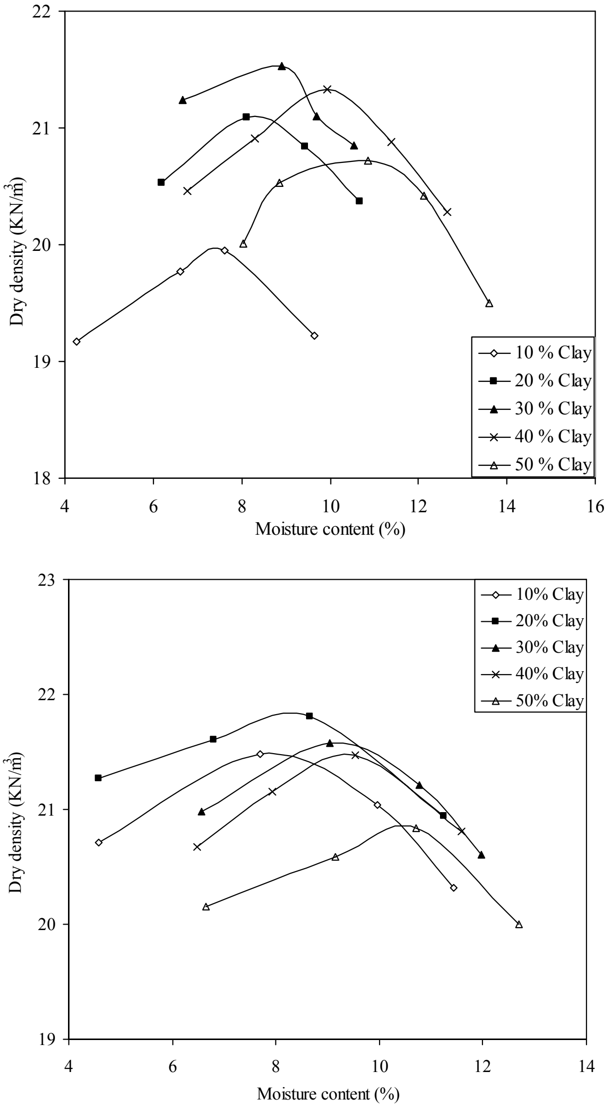

Figure 4. Variation of dry density with moisture content for clay-gravel and clay-sand-gravel mixtures

3 INCIPIENT MOTION OF COHESIVE SEDIEMENT MIXTURES

For cohesionless sediments the critical shear stress can be reliably determined by using any one of the versions of Shields' function from knowledge of grain density, size and gradation and fluid properties (Cao et al., 2006, van Rijn, 2007). However condition of incipient motion of cohesive sediments depends both on the complex mechanical characteristics such as shear stress and shear strength and the physico-chemical properties of the cohesive sediments. Amount and type of clay, antecedent moisture content, bulk density, unconfined compressive strength etc. were therefore considered by Kothyari and Jain, (2008) to be the easily measurable variables representing the factors controlling the erosion of cohesive sediments. Incipient motion condition of cohesive sediment was identified by a few investigators experimentally for the cohesive sediment mixture of clay-silt-sand using any of the following approaches.

(i) As per Kamphuis and Hall (1983), at low flow velocities, the cohesive sediment surface became streaked with a series of very fine, parallel lines, 2 mm to 3 mm apart, as if a fine wire brush has been passed over it in the direction of the flow. As the critical velocity approaches, the streaks disappear and erosion becomes apparent by the removal of large flakes from the surface.

(ii) Panagiotopoulos et *al.* (1997) determined critical shear stress of cohesive sediment bed under unidirectional and oscillatory flows as the shear stress due to flow at which the dislodgement of particles from cohesive beds begins in the forms of small clusters of various sizes.

Kothyari and Jain (2008) also presented the results from their experimental study for incipient motion condition of cohesive sediments consisting of clay-gravel and clay-sand-gravel mixtures. The details regarding experimental set-up, preparation of bed and experimental procedure are available in Kothyari and Jain (2008) and in Jain (2008). Three Stages of incipient condition of motion were visually identified namely: pot hole erosion, line erosion and mass erosion. The modes of initiation of motion changed mainly with clay percentages in the mixture, its antecedent moisture characteristics and the applied shear stress. The variables namely; clay percentage, void ratio and unconfined compressive strength of the sediment bed were noticed to be the main parameters controlling the incipient motion condition of the cohesive sediments. Figure 5 shows the bed surface showing initiation of motion of cohesive sediment in the form of mass erosion in case of clay-sand-gravel mixtures. In Fig. 5 P_c in initial clay percentage, e is void ratio and w is antecedent moisture content of the sediment bed and *UCS* is unconfined compressive strength of cohesive sediment bed.

In order to quantify the behavior at incipient motion condition of cohesive sediment in comparison to cohesionless sediment of similar bulk characteristics, Fig. 6 is prepared which depicts the variation of observed values of critical shear stress of cohesive sediment (τ_{cc}) with the arithmetic mean size of the corresponding cohesive sediment mixtures. The Shields' curve is superimposed on the Fig. 6 to compare the τ_{cc} values with the critical shear stress value of cohesionless sediment having similar arithmetic mean size as cohesive sediments. Almost all the observed τ_{cc} values for cohesive sediments fall much above than the Shileds' line indicating that for the given value of particle size, the critical shear stress of cohesive sediments is much larger than the same sized cohesionless sediment. Also increasing value of τ_{cc} with a reduction in particle size is followed for all the data. Similar finding were also observed by Raudikivi (1990) and Righetti & Lucarelli (2007) for the cohesive sediments without gravel. Further to identify the effect of unconfined compressive strength *UCS* on τ_{cc}, whole data are divided into three ranges based on *UCS* values. It is clear from figure that τ_{cc} is increasing function of *UCS*. Similar results have also been reported by Kamphuis and Hall (1983) for the case of clay-sand mixtures. The zones of different *UCS* values are depicted by dotted line as a few data points encroach into the neighboring zones particularly while clay percentage is higher.

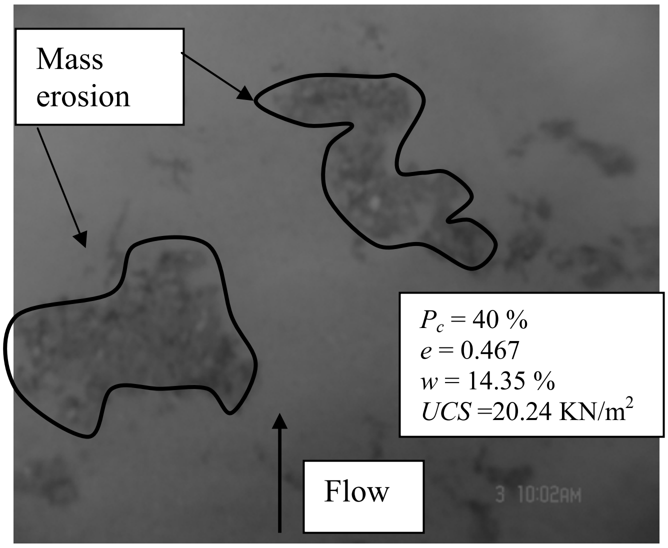

Figure 5. Bed surface showing initiation of motion in the form of "mass erosion"

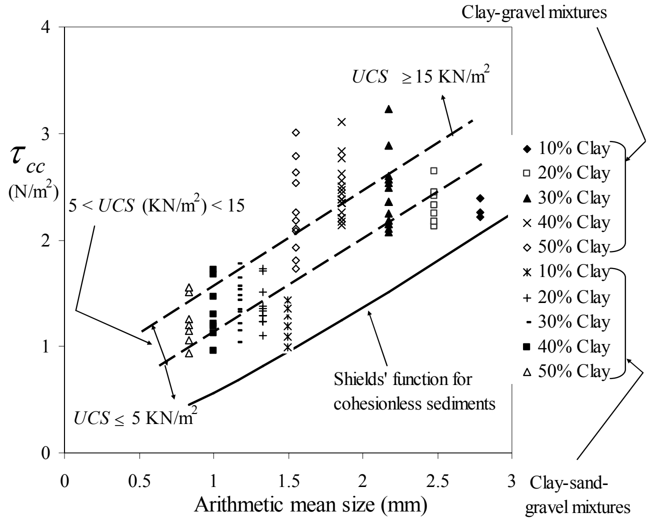

Figure 6. Variation of critical shear stress of cohesive sediment mixture with its arithmetic mean size

4 TRANSPORT OF COHESIVE SEDIMENTS

Due to complex and interactive behavior of clay, the bed load transport of cohesionless fraction present in cohesive sediments and suspended load transport of its cohesive fraction is considerably different from that of cohesionless sediments. The transport rate of cohesionless uniform and non-uniform sediments can be reliably determined by using any of the various methods available for its computations (Garde and Ranga Raju, 2006) by using the knowledge on grain density, size and gradation, flow and fluid parameters. However in case of cohesive sediments the variables namely; clay percentage and unconfined compressive strength of the sediment bed are the main parameters controlling the bed load and suspended load transport rate. Mitchener and Torfs (1996) studied the erosion of mud-sand mixture experimentally. The mud was added to sand in various percentages varying from 3 to 50% by weight. They observed mode of erosion to change from cohesionless to cohesive behavior even when low mud content is added to sand with transition is occurring in the region between 3% to 15% mud being present by weight. Jain and Kothyari (2009 & 2010) are the first to report the results of experimental study on the process of bed load and suspended load transport generated through the detachment of cohesive sediments consisting of clay-gravel and clay-sand-gravel mixtures. Two types of sediment mixtures were tested (i) fine gravel mixed with clay in proportions varying from 10 % to 50 % and (ii) fine gravel, fine sand in equal proportion (by weight) mixed with clay proportions again varying from 10% to 50% by weight. Transport characteristics of cohesive sediments varied with respect to initial clay percentage, antecedent moisture content in the sediment bed. For lower percentage of clay, transport of sediment mostly occurs by rolling of cohesionless sediment particles over the bed surface while the clay moved in suspension. However for sediment bed having higher clay percentages (above 20 %), detachment occurred in the form of thick flakes from the bed surface. At the end of experimental run longitudinal tiny channels appeared on significant portion on the bed surface representing the process of rill erosion in the cathcment surface (Kothyari et al., 1997) as shown in Fig. 7 for the case of clay-gravel mixture and clay-sand-gravel mixture.

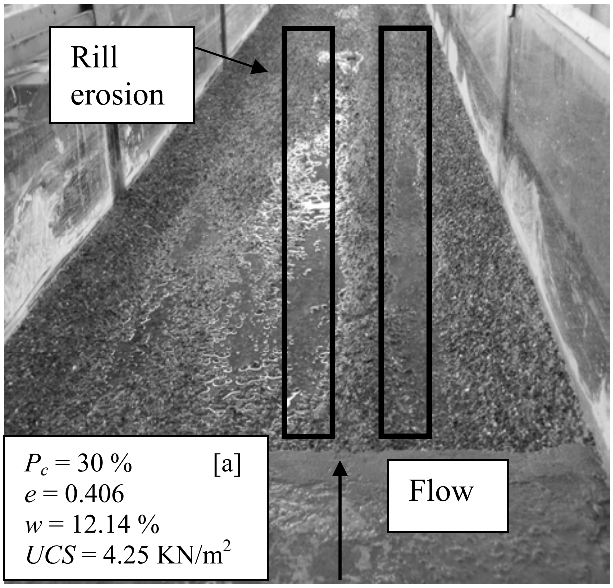

Figure 7 [a]. The Detachment pattern in cohesive sediment bed forming rill in clay-sand-gravel mixture

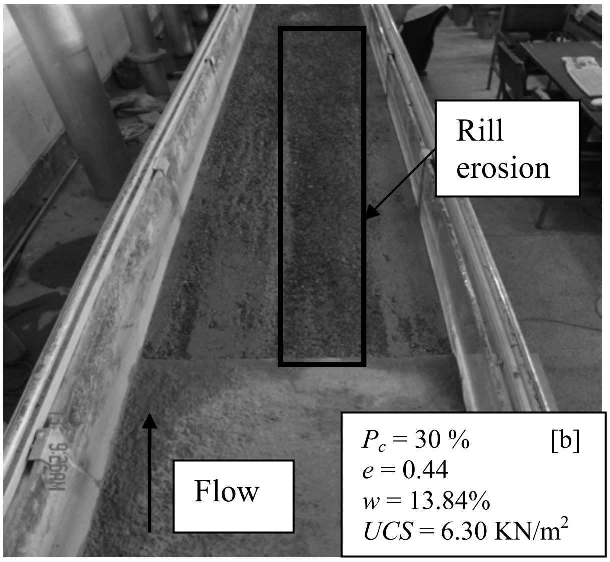

Figure 7 [b]. The Detachment pattern in cohesive sediment bed forming rill in clay-sand-gravel mixture

Depending upon the antecedent moisture conditions and the flow shear stress applied, the sediment detached by the flow in the form of lumps or chunks of the mixture of cohesive and cohesionless sediments of varying sizes and shapes. For still higher percentages of clay (*i.e.* 40 % or more) the detachment occurred in the form of lumps of the cohesive sediment. These lumps were of irregular geometry and size too as shown in Fig. 8.

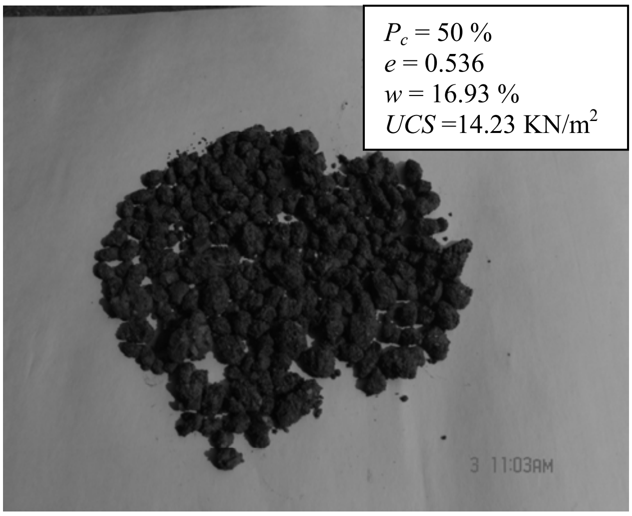

Figure 8. Lumps of sediments detached from cohesive sediment bed in case of clay-sand-gravel mixture

The inter comparison amongst Figs. 4 to 8 revealed that clay percentage, antecedent moisture content, bulk density and unconfined compressive strength of the cohesive sediment mixtures are the main factors controlling the erosion behavior of the cohesive sediment mixtures

Figure 9 shows the variation of bed load transport of cohesionless fraction present in cohesive sediment at various percentages of clay in clay-gravel mixtures. For a comparison the transport rate of gravel alone is also shown under the almost similar flow conditions. It is clear from the figure that transport rate of cohesionless fraction reduces with the presence of clay fraction in bed material and it reduces with increase of the clay percentage in bed material. Significant decrease in transport rate of gravel with time as seen in Fig. 9 is attributed to the reason that the channel bed profile degraded during the experimentation and hence shear stress due to flow at different sections reduced with time.

Further data are also being collected presently to study the size, shape and distribution of the lumps of eroded cohesive sediment mixtures formed under different conditions of flow and sediment mixtures. This would result in a better understanding of the erosion process of cohesive sediment mixtures.

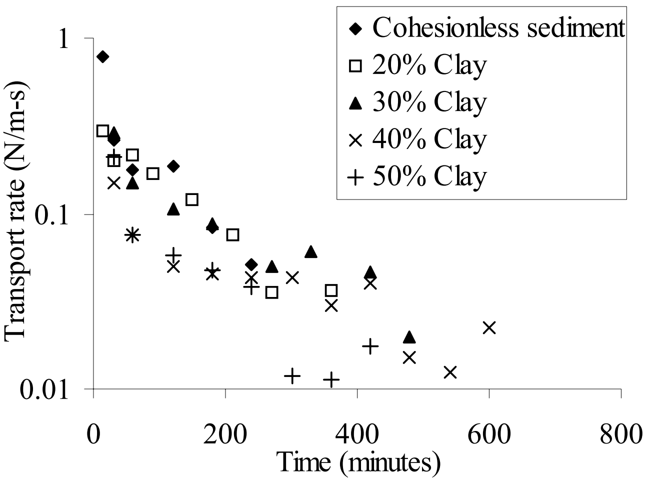

Figure 9. Variation in bed load transport rate of gravel with percentages of clay in the sediment bed

5 CONCLUSIONS

A review on the topic of erosion characteristics of cohesive sediment mixtures is presented. Very little research work is done so far on the topic erosion of cohesive sediment mixtures containing clay and gravel. Additional data on erosion behavior of cohesive sediment mixtures containing gravel is presented herein. The process of incipient motion condition, bed load and suspended load transport of cohesive sediment mixtures was found to be significantly different from that of cohesionless sediment under similar flow conditions due to complex and interactive behavior of cohesive sediment mixtures. Clay percentage and unconfined compressive strength of sediment bed are identified as the main parameter affecting the critical shear stress and transport of cohesive sediment. Three stages of incipient condition of motion were visually identified namely: pot hole erosion, line erosion and mass erosion which varied with respect to clay percentages, antecedent conditions and applied shear stress. The critical shear stress of cohesive sediment was found to increase with increase in clay percentage and unconfined compressive strength of sediment bed. The transport of cohesionless fraction present in the cohesive sediment mixture reduces with increase of clay percentage in sediment bed. The clay fraction of the cohesive sediment mixture always moved in suspension in the flow.

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