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INFLUENCE OF COHESION ON BED LOAD TRANSPORT OF SAND AND GRAVEL FROM DETACHMENT WITH BIMODAL SEDIMENT

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ABSTRACT

Experimental results on bed load transport rate measurements of sand and gravel from detachment of cohesive sediment mixtures with bimodal sediment are presented. The sediment used for experimentation consisted of fine gravel, fine sand in equal proportions mixed with varying proportions of clay from 10 to 50% by weight. Clay content and unconfined compressive strength of cohesive sediment were found to be main factors controlling the transport rate of gravel and sand generated through detachment of cohesive sediment mixtures. Based on dimensional considerations a relation is proposed to compute the bed load transport rate of sand and gravel occurring through its detachment from bed material made up of cohesive sediment mixtures. In the absence of cohesion, the proposed relation reduces to Almedeij et al. (2006) method for computation of bed load transport rate and bimodal cohesionless sediment mixtures.

Keywords: Bed load transport, cohesive sediments, cohesionless sediments, detachment, shear stress, unconfined compressive strength

1. INTRODUCTION

The evaluation of cohesive sediment detachment and transport rate by the flow of water is the topic of major importance for many hydraulic engineering related tasks like mitigation of soil erosion in catchment areas, reservoir sedimentation studies, stable channel design and river morphological modeling. It is also important for ecological investigations since cohesive sediment affects the heath of aquatic ecosystem by degrading water clarity and transporting pollutants. 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 well investigated and very well understood (Garde and Ranga Raju, 2000). However prediction of bed load transport with bimodal cohesionless sediment is still a problem of active research. The bed material in gravel-bed stream is usually well represented by either a unimodal or bimodal grain size distribution. The presence of two modes typically one of sand size and other of gravel size complicates the problem of bed load transport predictions (Wilcock, 2001). With the presence of cohesive material such as clay in gravel bed stream, the prediction of bed load transport with bimodal sediments becomes further complex.

Several investigations are available on erosion and transport of consolidated and unconsolidated uniform size cohesive sediments formed by clay material (Raudkivi, 1990). However the land surfaces and river bed material frequently consist of mixture of cohesive as well as cohesionless sediments like mixtures of sand, gravel and clay etc. Several studies are available to compute the bed load transport in case of non-uniform cohesionless sediments taking into account fractionwise computation viz; Patel and Ranga Raju (1996), Wu et al. (2000) etc. Almedeij and Diplas (2003) proposed an approach to predict bed load transport rates in gravel bed stream for a wide range of shear stress.

Almdeij et al. (2006) presented a method to compute the bed load transport rate of sand and gravel in a sediment mixture consisting of bimodal sediments. One approach to compute bed load transport rates in case of bimodal sediments is to divide the bed material into two unimodal fractions, each with a representative particle diameter (Kuhnle 1992, Wilcock, 1998). Bagnold (1980) suggested to use corresponding mode grain size to represent each of two unimodal components in case of sand-gravel mixture. The mode is appropriate choice for the unimodal component, because among the other size available, its motion is stable and it has the advantage of always having the highest percentages by weight (Almedeij and Diplas, 2003). Almdeij et al. (2006) opted for the simplest approach to carry out two separate computations of bed load, one for each mode, to determine the contributions of the respective components. No study is available so far to compute the bed load transport of bimodal sediments (sand and gravel) present in cohesive sediment mixtures. Therefore, the present investigation was taken up to study the effect of presence of cohesive material such as clay on detachment of bimodal cohesionless sediment consisting of mixtures of sand and gravel size particles.

2. EXPERIMENTAL PROCEDURE

2.1 *Experimental Flume*

An extensive experimental program was undertaken to study the influence of cohesion on and process of detachment and transport of cohesive sediment mixtures consisting of clay-sand-gravel. 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 8.5×10^{-3}. 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. A detailed description on experimental program and procedure followed can be found in Kothyari and Jain (2008) and Jain and Kothyari (2008). Only salient features of this experimental program are presented herein for completeness.

2.2 *Properties of the Cohesive Sediments*

Cohesionless sediments consisting of fine sand and fine gravel were used as base sediment. Clay was added in various proportions (10 to 50 %) to the base sediment to create cohesive sediments. 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 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, Sand had a mode size of 0.25 mm, while gravel had a mode size of 2.8 mm. Fig. 1 shows grain size distribution of bed materials. The relative density of sand and gravel was 2.65. 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, $\Phi_c = 21^0$ and relative density = 2.6. As per IS-1498, the clay was classified as *CI i.e.* clay with intermediate compressibility.

2.3 *Preparation of channel 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 and required dry density. 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 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 uniformity of the compaction throughout the test section. Prior to experimentation the prepared bed was saturated for 24 hours. The value of dry density, antecedent moisture content and unconfined compressive strength reported in the paper are measured at the completion stage of compaction or kneading.

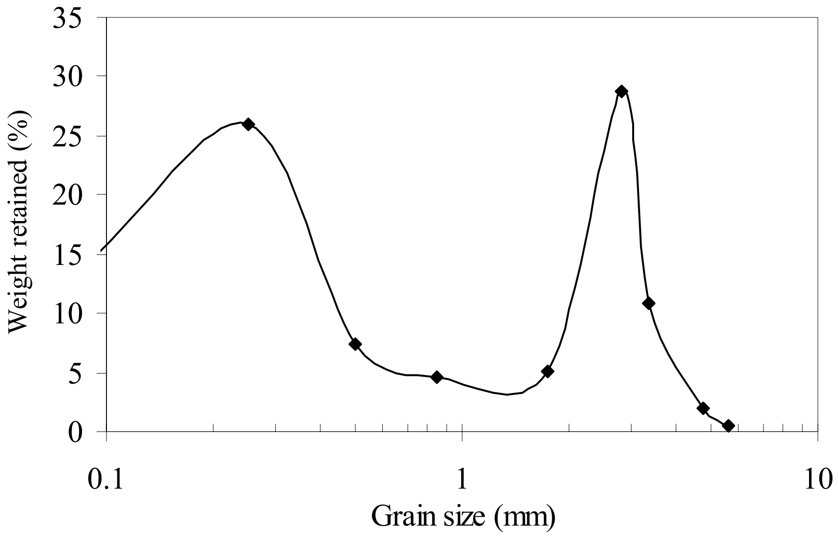

Figure 1 Grain size distribution of bed materials

2.4 *Experimental Procedure*

Desired discharge was allowed into the channel through the inlet pipe. Bed load portion of the detached material was measured by collecting the sediment in a trap placed at the end of the flume. The water surface elevations were observed by point 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. A total of 46 runs were taken corresponding to transport by detachment of cohesive sediments mixtures consisting of clay, sand and gravel. In all 353 observations were taken. Table 1 gives the range of sediment and hydraulic parameters collected herein.

Table 1: Range of sediment and hydraulic parameters collected transport by detachment of cohesive sediments consisting of clay-sand-gravel mixtures

P_c (%)	d_a (mm)	W (%)	γ_d (KN/m^3)	e (-)	UCS (KN/m^2)	h (m)	U (m/s)	S_f (-)	τ (N/M^2)	q_{Bg} (N/m-s)	q_{Bs} (N/m-s)
10.0 - 50.00	0.834-1.498	7.2-21.69	16.05-20.8	0.25-0.62	0.0-25.18	0.058-0.1891	0.479-1.126	0.001-0.0084	1.34 - 7.94	0.003-0.480	0.0005-0.0697

In Table 1, P_c is clay content, d_a is arithmetic mean size of sediment mixture, W is antecedent moisture content, γ_d is dry density, e is void ratio, UCS is unconfined compressive strength of sediment mixture, h is flow depth, U is mean velocity of flow, S_f is energy slope, τ is shear stress, q_{Bg} is transport rate of gravel by detachment, q_{Bs} is transport rate of sand by detachment.

3. ANALYSIS OF EXPERIMENTAL DATA

Detachment and transport rate of unimodal cohesionless uniform and non-uniform sediments can be determined adequately accurate by using any of various methods available in the literature for its computation (Garde and Ranga Raju, 2000) from knowledge of grain density, size and gradation, flow and fluid parameters. To quantify transport rates of cohesive sediments during the detachment in comparison to those of cohesionless sediments of similar grain density and grain size, the percentage of clay, sand and gravel in the bed material was computed first using the formulations for active bed layer at those time periods while the observations for flow and bed profiles were made (Jain and Kothyari, 2008). Using the computed friction slope from observed water surface profiles at these time intervals the shear stress was computed which corresponded to the consequently measured average detachment and hence the transport rate. The average detachment rate was determined based on a number of samples of bed load transport taken during the periods while energy slope remained practically constant.

As per Almedeij et al. (2006) the calculation of bed load transport rate for bimodal sediment mixture into two independent fractions of sand and gravel can be given as

$$Q_{bs}^{**} = \frac{1}{0.132\left(0.03\tau_{*s} / \tau_{*rs}\right)^{-0.35} + 10^{-9.59}\left(0.03\tau_{*s} / \tau_{*rs}\right)^{-7.95}} \tag{1}$$

$$Q_{bg}^{**} = \frac{1}{0.132\left(0.03\tau_{*g} / \tau_{*rg}\right)^{-0.35} + 10^{-9.59}\left(0.03\tau_{*g} / \tau_{*rg}\right)^{-7.95}} \tag{2}$$

Here

$$Q_{bs}^{**} = \frac{(G-1)Q_{bs}}{\sqrt{g}(hS)^{1.5}} \text{ and } Q_{bg}^{**} = \frac{(G-1)Q_{bg}}{\sqrt{g}(hS)^{1.5}} \tag{3}$$

where Q_{bg}^{**} is transformed dimensionless bed load transport of gravel, Q_{bs}^{**} is transformed dimensionless bed load transport of sand, Q_{bg} is volumetric bed load transport rate of gravel, Q_{bs} is volumetric bed load transport rate of sand, τ_{*g} is dimensionless shear stress of gravel mode size defined as $\left(\frac{\gamma_f hS}{(\gamma_s - \gamma_f)D_g}\right)$, τ_{*s} is dimensionless shear stress of sand mode size defined as $\left(\frac{\gamma_f hS}{(\gamma_s - \gamma_f)D_s}\right)$. τ_{*rg} is reference shear stress for gravel mode, and τ_{*rs} is reference shear stress for sand mode. In above D_g and D_s are the mode sizes of gravel and sand respectively. The reference shear stress for the mode size of sand and gravel is determined from the plot of dimensionless bed load transport parameter Q_{bi}^{*} and shear stress τ_{*i}, taking the shear stress corresponding to low reference value of dimensionless bed load transport parameter $Q_{bi}^{*} = 0.002$ (Parker *et al.*, 1982). Here

$$Q_{bi}^{*} = \frac{(G-1)Q_{bi}}{i_b\sqrt{g}(hS)^{1.5}} \tag{4}$$

$$\tau_{*i} = \frac{\gamma_f hS}{(\gamma_s - \gamma_f)d_i} \tag{5}$$

Q_{bi} is the volumetric bed load transport rate per unit width for sediment size d_i.

4. DIMESIONAL CONSIDERATION

An examination of various analytical and semi-theoretical approaches on bed load transport of cohesionless sediments revealed that transport rate in the case of cohesionless sediments is a function of bed shear stress and particle size only. However in the case of cohesive sediments because of physico-chemical properties transport rate due to detachment is a function of additional factors such as; clay percentage, dry density, unconfined compression strength etc. (Jain and Kothyari, 2008). Keeping these in view the following functional form of relationship is written for the computation of bed load transport rate caused by detachment in the case of cohesive sediments

$$q_{bc,i} = f(q_{b,i}, P_c, d_a, C_u, \theta_c, \theta_{sh}, \gamma_d, \gamma_w, \Delta\gamma_s, UCS') \tag{6}$$

Here $q_{bc,i}$ is bed load transport rate of given size fraction of cohesive sediment mixture, $q_{b,i}$ is bed load transport rate of the same size fraction for cohesionless sediment under the same flow conditions, C_u and θ_c are the cohesion and angle of internal friction for clay at optimum moisture content, θ_{sh} is angle of repose/internal friction of cohesionless sediment for the respective sediments present in the mixture, γ_d is dry density of the cohesive sediment mixture and d_a arithmetic mean size of the bed material mixture, $\Delta\gamma_s = \gamma_s - \gamma_w$, with γ_s being specific weight of sediment and γ_w is specific weight of water. The UCS' is defined as $UCS' = (P_c/P_{co})UCS$; where P_{co} is the initial percentage of clay in the bed material and P_c is clay percentage in bed material concurrent to the time of bed load transport rate observation which was determined based on the concept of the active bed layer. Parameters P_c, C_u, θ_c, θ_{sh}, $\Delta\gamma_s$, d_a can be expressed into dimensionless form as below (Ansari et al. 2002, 2003)

$$C_* = \frac{P_c C_u}{\Delta\gamma_s d_a} \tag{7}$$

and $$\phi_* = \frac{P_c \tan\theta_c + (1 - P_c)\tan\theta_{sh}}{\tan\theta_{sh}} \tag{8}$$

Variable UCS' can also be written in dimensionless form as (Kothyari and Jain, 2008)

$$UCS^* = \frac{UCS'}{\Delta\gamma_s d_a} \tag{9}$$

As per Jain and Kothyari (2008) the variables can be arranged in the following non - dimensional form

$$\frac{q_{bc,i}}{q_{b,i}} = f\left(\frac{C_*}{\phi_*}, UCS^*, \frac{\gamma_d}{\gamma_w}\right) \tag{10}$$

The range of γ_d / γ_w covered by the present data is from 1.54 to 2.12. The analysis of the data indicates that this small range of variation in γ_d / γ_w does not fully explain the variation in $q_{bc,i}/q_{b,i}$ therefore the variable γ_d / γ_w was dropped from the further analysis and the new functional relationship for $q_{bc,i}$ is written as

$$\frac{q_{bc,i}}{q_{b,i}} = f\left(\left(1 + \frac{C_*}{\phi_*}\right), (1 + UCS^*)\right) \tag{11}$$

It is worthwhile to use the variable $1+(C_*/\varphi_*)$ instead of (C_*/φ_*) so that $q_{bc,i} = q_{b,i}$ while $P_c = 0$. With similar consideration the variable $(1+UCS^*)$ is used instead of UCS^* to account for both hard consistencies and soft consistencies of the cohesive sediments. The functional relationship shown by Eq. (11) can be used to develop a relation to compute the bed load transport rate caused by the detachment of the cohesive sediments. The value of $q_{b,i}$ to be used in

Eq. (11) can be determined by using an appropriate relationship for bed load transport of the bimodal cohesionless sediment mixture. Relationships proposed by Almedeij et al. (2006) are used here to compute the bed load transport in case of bimodal cohesionless sediment mixtures.

Analysis of the available data revealed that $q_{bc,i}/q_{b,i}$ is inversely proportional to $(1+C_*/\phi_*)$ for the sediment mixtures used in present study as shown in Fig. 5. Analysis also revealed that $q_{bc,i}/q_{b,i}$ is inversely proportional to $(1+UCS^*)$ as shown in Fig. 6.

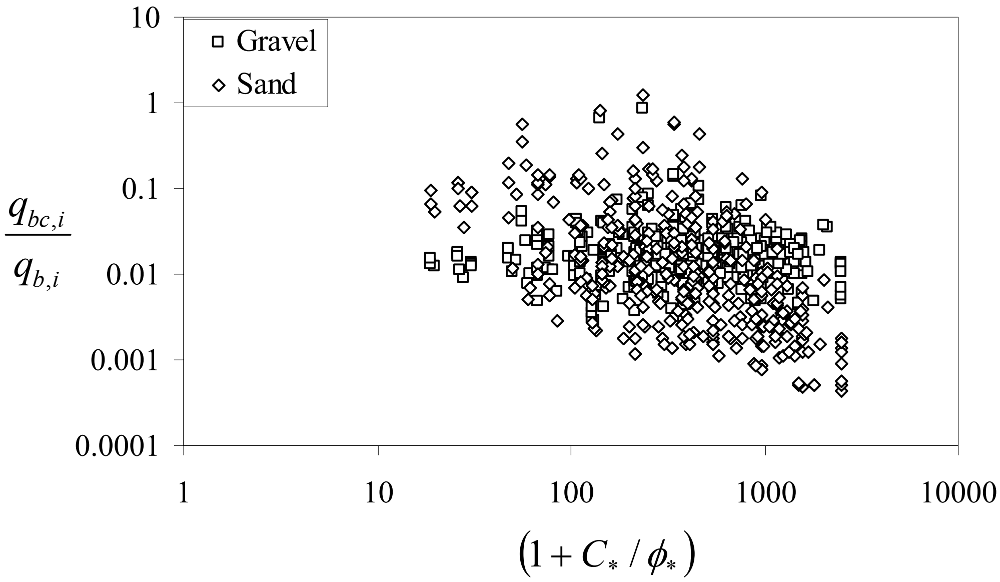

Fig. 5 variation of $q_{bc,i}/q_{b,i}$ with $1+(C_*/\varphi_*)$

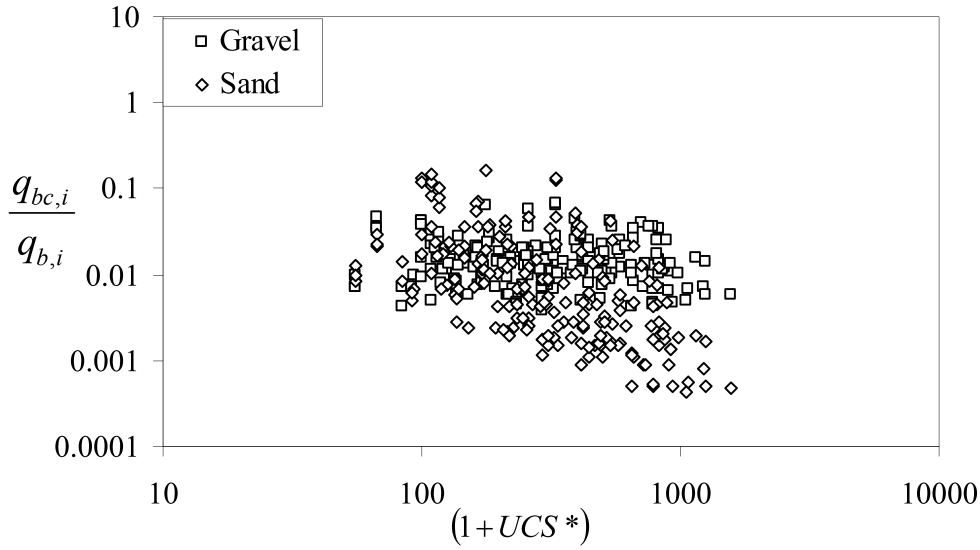

Fig. 6 variation of $q_{bc,i}/q_{b,i}$ with $(1+UCS^*)$

After making number of trials and taking all dimensionless parameters together following equation is proposed to compute the bed load transport of gravel and sand generated through detachment of cohesive sediment mixtures

$$q_{bc,i} = q_{b,i}(1 + C_* / \phi_*)^{-11/20}(1 + UCS^*)^{-3/10} \tag{12}$$

To check righteousness of proposed equation, the mean absolute square error (*MASE*) is computed as per Almedeij and Diplas (2003) which is given as

$$\text{MASE}= \frac{\sum_{i=1}^{n} q_{ri}}{n} \tag{13}$$

Here n is total number of data and

$$qri = \frac{q_{bc,i(predicted)}}{q_{b,i(observed)}} \quad \text{if } q_{bc,i}\text{ (predicted)} > q_{bc,i}\text{ (observed)}$$

$$qri = \frac{q_{bc,i(observed)}}{q_{b,i(predicted)}} \quad \text{if } q_{bc,i}\text{ (observed)} > q_{bc,i}\text{ (predicted)}$$

The Eq. (13) indicates that the closer the *MASE* value to one, better the accuracy of an equation, with *MASE* =1 representing the condition for perfect agreement. The value of *MASE* is 3.69 for bed load transport of gravel and it is 4.07 for bed load transport of sand caused through detachment of clay-sand-gravel mixtures. The value of *MASE* obtained albeit is large but similar to the values obtained by Almedeij et al. (2006) for the bed load transport of bimodal cohesionless sediments.

Again to check the goodness of fit of the proposed equation, the computed values of the bed load transport rate are plotted against the corresponding observed bed load transport rate values as shown in the Fig. 7. The scatter of results by the proposed method as seen in Fig. 7 albeit is large, but is acceptable in the context of similar results normally reported in the literature on sediment transport studies (Yang et al. 1996, Almedeij and Diplas, 2003).

It is however, significant to note that in the absence of cohesion, the proposed relation for bed load transport rate gets transformed to the Almedeij et al. (2006) method for bed load transport rate of bimodal cohesionless sediment mixtures. Several other dimensionless groups were also used to study the variations in $q_{bc,i}/q_{b,i}$. It should be noted that only the best results obtained are reported above.

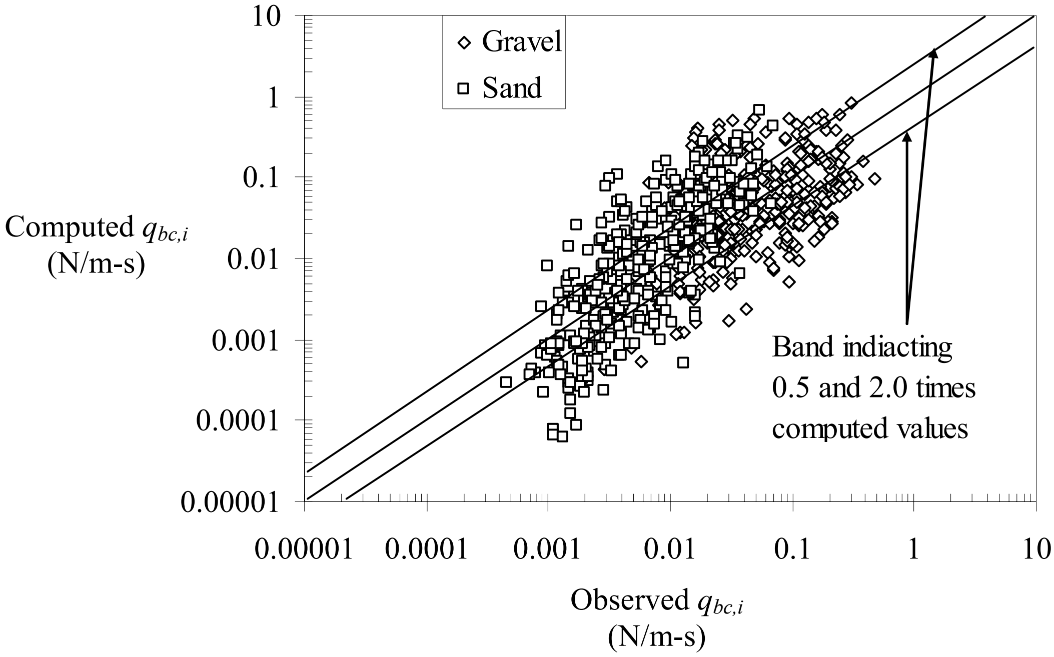

Fig. 7 Observed versus computed bed load transport rate of gravel and sand

5. CONCLUSIONS

Numerous experiments were conducted to study the bed load transport rate caused by the detachment of cohesive sediment beds made up of clay mixed in varying proportions with bimodal cohesionless sediments. Sediment mixtures were consisting of clay mixed in varying proportion (10 to 50 % by weight) with fine sand and fine gravel (each in equal proportion). The proportion of clay fraction in the mixture was found to significantly affect the rate of bed load transport. Based on dimensional considerations the functional forms of the relationship were derived to compute bed load transport rate of gravel and sand present in cohesive sediment mixtures.

Further Eq. (12) is developed for estimation of the transport rate of sand and gravel by detachment from clay-sand-gravel mixture. The significant reduction in the transport rate which occurs in the presence of clay is amply reflected by the present study. In the absence of cohesion in the mixtures, the proposed relation reduces to the method of Almediej et al. (2006) for the computation of bed load transport rate of bimodal cohesionless sediments under the given flow conditions.

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