Study of the flow of silted water passing through gravel deposit

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Abstract: The results and their analysis from the experimental investigation of infiltration of fines into mobile gravel bed have been presented in this paper. Water carrying fine materials in excessive quantity when passes through the rivers with gravel on its bed, the flow releases the silt that infiltrates into the pores of the gravel deposit and gradually gets accumulated there. Several experimental investigations were carried out on a recirculating tilting flume of length 13m, width 40cm and depth 50cm to investigate the fines infiltration and deposition into the gravel deposit and its consequences on the bed material movement and other associated properties of open channel flow. Uniform sized clean gravels of size 1.9mm and 0.062mm sized silt were used for experimental works. Uniform flow conditions were maintained during all the experimental runs. Fines concentration in the flow was successively increased in each run. It was observed that in each run a definite amount of silt infiltrated into the bed. It was also observed that there was certain variation in the transport of gravel with the silt concentration as the bed was mobile. This paper contains the analysis of the data thus obtained with reference to the present and earlier works.

Keywords: Silt, Bed load, Concentration, friction factor, infiltration

1. Introduction:

An alluvial channel always remains in dynamic equilibrium by changing its width, slope. This happens either by the transport of the parent bed material from a reach or deposition of the bed material from upstream. One of the major factors responsible for this phenomenon is the change in flow of water in the channel. Flow quantity along with its velocity/depth and bed material itself i.e. fluid and the bed characteristics are main driving forces for the movement of bed materials. In addition if the flow is loaded with fine sediment (here silt), the fluid characteristics changes and hence it affects the entire hydraulic system of the channel. Similar situation can be frequently observed during the rainy season in the rivers of mountainous region where bed is composed of gravel. When silted water flows through the mobile gravel deposit, the bed load transport rate changes as being observed by the previous researchers. The resistance offered by the flow also differs as compared to that of clear water flow. Another major effect of flow of silted water can be observed on the production and survival of Salmon fish and several other aquatic lives. Silted water flow also put an adverse impact on social and economic conditions of the nearby civilization. The present paper is an attempt to understand the above discussed issues caused by the flow of silted water.

2. Review:

The term bed load usually describes particles flowing in fluid that are transported along the bed of the channel. Bed load particles may move by rolling, sliding or by periodic bouncing (saltation). When the flow condition exceeds the criteria of incipient motion the bed load movement starts. Silt normally lies in the size range of 60 microns and hence termed as wash load. There are several definitions of wash load. Some researchers have defined wash load in terms of its own particle size or size of the bed particles and some has defined wash load based on the carrying capacity of the flow. Despite of all theories and definitions, silt is always considered as wash load and hence termed as wash material as well.

There are numerous bed load transport equations developed by several investigators. But there are two broad approaches of bed load prediction; those calculated by force and those by power. Based on these two approaches three types of bed load transport equations are developed; empirical, semi-theoretical and equation based on dimensional consideration. Some examples of empirical equations are schoklitsch [1], Meyer-Peter and Mullar [2]. Einstein [3, 4], Kalinske [5], Bagnold [6] are some semi-theoretical bed load transport equations. Rotner [7] is an example of bed load transport equation based on dimensional consideration. In spite of the availability of plethora of bed load transport equation hardly very few equations give more or less similar results for a particular scenario. For example Yalin [8] states "There is no room here to go through all these formula, nor it is necessary, for many of them now have become historical meaning". The condition these days has not changed; even the bulk of such equations being continuously added.

There are basically two main processes that cause a river bed to clog with fine sediments. First as mentioned by Owens et al [9], disturbance in watershed caused by logging, mining, and agriculture etc lead to an increase in the amount of fines delivered to the river system. Second as mentioned by Karlinger et al. [10], Andrews [11], Van Steeler and Pitlic [12], flow regulation sometimes reduces the transport capacity of the river leading to deposition of fines on the bed and bank and hence causes potential change in the river morphology. Intrusion of fines/silt into the river bed has an adverse impact on the entire river ecosystem. A seal of silt on the channel reduces the oxygen supply necessary for Salmon eggs and alevin to develop properly. Silted water block an access of sunlight and sediment on the bed can reduce attachment area for algae, limiting primary production [Osmundson et al. 13]. Several other aquatic lives which normally habitat and incubate in the pores of gravel deposit gets badly affected.

When silted water flows through gravel deposit, the bed load transport rate is different than that if the flowing water is clear. The reason behind this change in bed load transport rate, as attributed by many researchers can be given to the possible change in the frictional resistance due to the presence of fines/silts in the flow. Again frictional resistance gets affected in two ways; dampening of the turbulence and formation of bed forms. Vanoni [14], Einstein and Chein [15], Cellino and Graf [16] etc observed decrease in resistance in presence of suspended load while on other hand Yano and Daido[17], Ippen [18], Imamoto et al. [19] stated increase in frictional resistance by silted water compared to clear water flow. While Arora et al [20] and Khullar [21] observed conditional increase or decrease in the resistance. And hence accordingly the bed load transport rate also changes with the silt concentration.

It has been observed by several investigators that fines infiltrate into the pores of the gravel deposit and gradually piles up to the surface unless it's being flushed by relatively clear water. But the clear water normally doesn't clean up all the fines/silt infiltrated into the gravel bed. Several flume studies have shown that fines will infiltrate a clean gravel bed regardless of transport mode [Beschat and Jackson 22, Diplas and Parker 23]. Fine sediment infiltration and deposition increases with supply until the bed is fully covered with sand [Diplas and Parker 23]. The depth to which the fines normally infiltrate is called an active bed layer. Simons et al. [24] observed clay infiltration down to the flume bottom. Einstein [25] observed similar results with silica flour as wash material. Beschta and Jackson [22] observed fines infiltration down to bottom in case of finer sand as filler material and only surface deposition in case of coarser sand. Frostick et al. [26] observed more fine sediment infiltration in coarser deposit than finer material deposit. Khullar [33] also observed limited depth infiltration by flowing silt. Sower and Sower [27] mentioned that the relative size of settling fines and voids of gravel bed is the main controlling factor for fines infiltration.

3. Experiment:

Hydraulic Engineering lab of the Indian Institute of Technology Roorkee was selected for all the experiments. A tilting flume of *13m* length, *0.40m* width and *0.60m* depth was selected for the experiments. The bottom of the channel was made of steel and fibre and sides of transparent glass. Water was supplied to the channel by a centrifugal pump. In the discharge inlet pipe, a well calibrated orifice was installed to measure the discharge entering into the flume. Baffle walls, boulder layer and other energy dissipating the excessive turbulence at the upstream of the flume. Manually operated tail gate fitted at the downstream end of flume to control the depth in the flume.

Uniform size gravel passing through *2mm* sieve and retaining on *1mm* sieve was used to pave the bed of the flume. The median size of the gravel was *1.9mm* with standard deviation *0.90*. Similarly silt passing through *125microns* and retaining on *45microns* was selected as filler material. The median size of the silt was *0.062mm* with standard deviation *1.21*.

Table1. Properties of materials used in experiments

Material	**d_{50}**	**d_{65}**	**σ_g**
Gravel	1.9mm	1.92mm	0.905
Silt	0.062mm	0.072mm	1.21

Washed gravel was laid on the bed of the channel to *15cm* depth. Gravel bed was thoroughly levelled with an wooden template and checked with point gauge. Before going for silt laden run one experiment with clear water was done. This run was basically to get a reference set of data for further comparison. A reference set of data included velocity of flow, bed load transport rate, turbulence parameters. After clear water run, several experiments with silted water were carried out. In each successive runs, the amount of silt added to flow were progressively increased to increase the silt concentration in the flow. The amount and duration of silt feeding were decided such that concentration should not cross the limiting value and at least *3-4* equilibrium conditions were achieved during the run. During the run, widths integrating suspended samples were taken at the end of the flume with the help of sampler to check the change in concentration of flow with time. Also depths integrating suspended samples were taken from two locations (*3m & 9m)* in the channel to check the vertical distribution of silt concentration. (Temporal and vertical variation of the silt concentration are not discussed in this paper). During the run, bed load samples were also continuously collected. At every half an hour interval collected bed load was measured at fed back at the upstream of flume to maintain sediment continuity. On the completion of the run, water was allowed to dry from the flume. Then bed samples from top to bottom of *2cm* slice were taken from three locations (*3m, 6m & pm)* along the channel. These samples were washed with clear water and water was allowed to dray to obtain the percentage of silt availability in each slice of bed sample at different locations.

4. Results and Analysis:

The flow was above incipient motion condition, hence bed was observed to move with the flow. Those bed materials were collected at the downstream in a net bag. At every half an hour interval, that bag was replaced with another one. This used to take hardly few seconds. Hence it is assured that there was almost no loss of bed load during the net bag changing process. The bed load collected in the bag was weighted and converted into dry weight by multiplying it by predetermined conversion factor. Table 2 below shows the variation of equilibrium bed load transport rate with successive runs.

Table 2. Bed load transport rate of various runs at different wash load concentration

Run No.	Bed load transport rate (q_B X 10^3) N/m-s	Concentration (C) PPM
C1	97.48	2
1	103.63	97
2	109.75	146
3	115.81	833
4	114.86	2173
5	124.47	3454
6	132.06	4611
7	137.73	6239
8	152.12	7953
9	162.15	9165

Fig.1. Change in bed load transport rate with increase in the wash load concentration

Figure 1 is a clear evident of increase in the bed load transport rate with increase in silt concentration in the flow. There seems to be slightly ups and downs in the equilibrium transport rate with increasing silt concentration. Nevertheless, in general it's showing an increasing pattern. To plot in the logarithmic scale, clear water concentration is arbitrarily considered as 1 as the log graph does not plot the zero value. Another point to be noted is that the rate of increment of bed load transport is not uniform. Since no significant bed form development was observed in any of these experiments, the only possible reason for the increase in the bed load transport rate can be given to the reduction in the friction factor. As per Darcy-Weisbach friction factor equation, friction factor is inversely proportional to the square of the flow velocity. And when the velocity increases, the bed load transport rate may increase. We are not yet sure whether friction factor is increasing or decreasing with the increase in silt concentration. In the succeeding section, the change in the friction factor will be analysed.

The observed bed load transport rate for a particular hydraulic condition is now checked with some of the well known bed load transport equation. Two equations which are formed for prediction of uniform bed load transport and two equations developed for non-uniform materials are selected. Since these later equations have the provision to be used for uniform sediment, these two equations are also selected. The models thus selected are Meyer-Peter and Mullar [2], Misri et al. [28], Patel and Ranga Raju [29] and Khullar [34]. Ning Chien [30] proposed a more simplified version of Meyer-Peter and Mullar [2] equation and also mentioned that this equation gives result as satisfactory as Einstein more rational formula if single characteristics size that represents bed material is used. Ning Chien [30] simplistic form is;

$$\tau'_{\text{¿}} = \frac{\gamma_f R'_b S}{(\gamma_s - \gamma_f) d_a} (1)$$

$$\varnothing = 8(\tau'_{\text{¿}} - 0.047)^{1.5} (2)$$

$$\varnothing = \frac{q_B}{\gamma_s}\sqrt{\frac{\rho_f}{\rho_s - \rho_f}\left(\frac{1}{g d^3_a}\right)^{\frac{1}{2}}} (3)$$

Where,

$$R_b = \left(\frac{U n_s}{\sqrt{S}}\right)^{\frac{3}{2}} \wedge n_s = \frac{d_{90}^{\frac{1}{6}}}{26}$$

Meyer-Peter and Mullar [2] divided total shear stress into two parts and mentioned that one which is responsible for bed movement is the grain shear stress only. Based on this concept Misri et al. [28] proposed new relationship between τ'_* and ϕ.

$$\varnothing = 4.6 \times 10^7 \tau'^{8}_{\text{¿}}\ for\ \tau'_{\text{¿}} \leq 0.0 \qquad (4)$$

and

$$\varnothing = \frac{8.5\tau'^{1.8}_{\text{¿}}}{\left[1 + 5.95 \times 10^{-6} \tau'^{-4.7}_{\text{¿}}\right]^{1.43}}\ for\ \tau'_{\text{¿}} \geq 0.065 (5)$$

If the bed is made of uniform sediment each particle is supposed to be subjected with same shear stress by the flowing water. But in case of non-uniform sediment finer particles are less subjected as they are sheltered by the coarser particle where as coarser particles are exposed and hence subjected to more shear stress than finer one. Hence Patel and Ranga Raju [29] and Khullar [34] considered a shelter- cum-exposure factor ξ in their equations. They also mentioned that if the bed is uniform, ξ can be taken as unity and same equations can be used for bed load transport of uniform sediment. The dimensionless bed load transport rate for any size fraction in a mixture as proposed by them is

$$\varnothing = f\left(\frac{\tau'_o}{\Delta \gamma_s d_1},\right)(6)$$

Fig.2. Comparison of observed transport rate with the above mentioned four models

Figure 2 is the comparative study of the bed load transport rate as observed and as found using various well known equations. What is clearly seen is that observed bed load is lesser than that predicted by almost all bed load transport formulae. The least close predictions are by Meyer-peter and Mullar [2] and Patel and Ranga Raju [29]. The predictions by other two formulae are almost same till *2173PPM*. That is when τ'_* value exceeds *0.065* limit, it under predicts the transport rate. Though not exactly, but Khullar [34] equation suits well among these methods for this particular study.

For the present study, the friction factor is being calculated by the Darcy-Weisbach equation.

$$f = \frac{8g R_b S}{U^2}(7)$$

Arora et al. [20] and Khullar [21] criteria have been checked here. Arora et al. (1986) criteria says that compared to the friction factor of clear water flow, friction factor for sediment laden flow increases with increase in sediment concentration if $\frac{C\omega}{US} \geq 1200$; and decreases with increase in sediment concentration if $\frac{C\omega}{US} < 1200.$ This criterion when checked by Khullar [21] for his own data found to be unsatisfactory and hence involved a new term and came with new equation. The inclusion of this new tern (s-1) to understand the resistance was earlier suggested by Einstein and Chien [31] and Parker and Coleman [32]. Khullar [21] friction factor predictor equation is;

$$1 - \frac{f}{f_0} = 10^{-5}(s-1)\frac{C\omega}{US}(8)$$

Fig 3. Variation of friction factor with Cω/US for alluvial channel [Arora et al. 20]

The friction factor for silted water flow is continuously decreasing with increase in concentration. But it doesn't satisfy the criteria of Arora et al. [20]. For $\frac{C\omega}{US} \geq 1200$ friction factor is not increasing with increase in concentration. Khullar [21] has proposed a relationship to find the friction factor of offered by flowing water carrying silt. The relationship is

$$1 - \frac{f}{f_0} = 10^{-5}(s-1)\frac{C\omega}{US}(9)$$

Fig. 4. Comparison of observed and computed friction factor [Khullar 21]

Figure 4 shows the considerable difference between observed and computed at higher concentration. This plot also tells that calculated value is lower than that observed. It's observed that maximum under estimation of friction factor is around 14% only. For most of the concentration, the predicted friction factor do not differ more than 10% than its observed value.

During these experiments, it was observed that silt infiltrated only halfway down to the gravel deposit. Silts that infiltrated into the gravel gradually started filling the gaps and making a seal to prevent the later incoming silts to move beyond that level. This is how the silt gradually accumulated up to the top surface. As mentioned earlier, bed samples were taken from three locations and different depths. Table 3 below shows the variation of silt at three locations for the last experimental run.

Table 3 %age of silt infiltrated at different sections of flume after last experimental run

Depth from top (cm)	At 3m	At 6m	At 9m
0-1	21.66	20.99	21.12
1--3	17.27	18.05	13.00
3--5	7.57	7.68	9.24
5--7	7.24	6.70	7.05
7--9	7.35	5.42	6.79
9--11	4.41	4.69	2.28
11--13	-	-	-
13--15	-	-	-

Fig. 5. Shows increasing percentage of silt at different depths at 3m section of flume with successive runs with increasing concentration

With each successive runs the silt availability at different depths at *3m* downstream from channel inlet is progressively increasing. The maximum accumulation of silt is observed at the top surface and the least at around *11cm* from top. So here in this present study its can be said that silt infiltrated down to around 50 times the mean size of the gravel. From the data it is also observed that the total quantity of silt (in terms of kgs) has also increased at each section with each successive runs.

Table 4 Amount of silt (Kgs) accumulated at different sections with successive runs

Run	At 3m	At 6m	At 9m
Run 1	0.47	0.42	0.39
Run 2	0.75	0.79	0.66
Run 3	0.77	0.73	0.7
Run 4	1.04	0.95	0.94
Run 5	1.2	1.08	1.06
Run 6	1.27	1.22	1.13
Run 7	1.34	1.27	1.13
Run 8	1.5	1.4	1.38
Run 9	1.73	1.58	1.51

Fig. 6 Variation of silt accumulation at three locations

Figure 6 is an evident of maximum amount of silt infiltration at section *3m* away from channel inlet and the lowest accumulation at the extreme downstream section. This also indicates that when silted water flows, it gradually loses its concentration. The flow contains less amount of silt towards flume end and hence less infiltration as it moves downstream.

5. Conclusions:

A total of ten set of experiments were conducted using *1.9mm* uniform gravel as bed material and *0.062mm* uniform silt as filler material. The observed bed load transport rate continuously increased with increase in the silt concentration in the flow. And the reason for this increase is attributed to the decrease in the friction factor which is also proved by the Darcy-Weisbach equation. Arora et al. [20] criteria not found to be satisfactory for this present study where as Khullar [21] friction load predictor equation gave better result with some exception at just few points. Khullar [34] and Misri et al. [28] bed load transport gave better result for the transport rate calculation. Silt infiltrated down to a depth around 50times the size of bed material and the maximum quantity of silt accumulation was observed on the top surface of the upstream section of the channel.

6. Notations:

C	Concentration (ppm)
d_a	Actual size of sediment
d_{50}	Median size of sediment
f	Friction factor for sediment laden flow
f_0	Friction factor for clear water flow
$\mathbf{q_B}$	Bed load transport rate
R_b	Hydraulic radius w.r.t. bed
R'_b	Hydraulic radius w.r.t. grain resistance
S	Bed Slope
s	specific gravity of sediment
U	Flow Velocity
τ'_*	Dimensionless average shear stress corresponding to grain
σ_g	Standard deviation
γ_f, γ_s	Specific weight of water and sediment respectively
ϕ	Dimensionless bed load transport rate
ω	Fall velocity
ξ	Shelter-cum-exposure factor

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