Available online at www.elixirpublishers.com (Elixir International Journal)

Civil Engineering

Elixir Civil Engg. 91 (2016) 38310-38314

ISSN: 2229-712X

Bed Load and Shear Stress in Open Channel Sediment Flow

Sumit Gandhi, Dushyant Pal and Manvender Singh

Department of Civil Engineering, Jaypee University of Engineering and Technology, Guna, India.

ARTICLE INFO

Article history:

Received: 24 December 2015;

Received in revised form:

5 February 2016;

Accepted: 11 February 2016;

Keywords

Shear Stress,
Bed Load,
Uniform Sediment,
Non-uniform Sediments,
Empirical Modelling.

ABSTRACT

Present study deals with the bed load transport and shear stress with uniform and non-uniform sediments in an open channel under different experimental conditions. Effort has been made to analyse extensive experimental results in comparison with the existing theories given by the various eminent researchers for both the types of sediment materials. Empirical relations are proposed by dimensionless approach with the help of Buckingham-π theorem in terms of dimensionless shear stress and bed load transport parameter. Results are compared and vaidated with Meunier (2006) and Roorkee's approach [i.e. Gilbert (1914), Pazis & Graf, Paintal (1977), Misri et. al (1984), Ranga Raju & R. J. Garde (1986)] for both uniform and non uniform sediment material.

Introduction

Bed load transport has been the subject of extensive research since the pioneering work of Du Boys (1879) and others. Till now one may hope to compute the bed load transport of uniform sediment only to a fair degree of accuracy; however natural river sediments are generally non uniform and analysis of bed load movement is quite complex. Smaller particles sheltered by the bigger ones and are therefore transported at a relatively smaller rate. On the other hand, the bigger particles experience larger dynamic forces than they would if they were in a uniform sediment bed and are consequently transported faster. At low shear stresses the coarser sediments may not move at all, resulting in a state of partial transport.

Study of the sediment movement for a hydraulic engineer is important because they come across various type of the problems (land erosion, silting of reservoir, degradation, aggradations, etc.) related to rivers and channels. Different studies shows the characteristics of sediment & its movement mainly depends upon the velocity of flow, size of the sediments, type of the material (uniform and non-uniform), shear stress and bed load.

The problems of the sediments are varied and complex. Synthesis knowledge from field methods and practices will be valuable. So empirical modeling is done and it is subjected to compare with the existing results of the various eminent researchers. Results shows approximately similar pattern of bed load for the both uniform and non uniform sediment material.

Meyer-Peter and Muller (1948) proposed the empirical relation for uniform material on the basis of excess shear stress. However Roorkee's approach (1984, 86) was based on grain shear stress. Further, Einstein (1942, 50) and Meunier et. al (2006) shows some semi theoretical approach and given due importance to mean velocity for accurate analysis.

A Dimensionless analysis are tried and proposed in the present study for both uniform and non-uniform sediments following the contribution of other authors as presented in below sections.

Theory

Du Boys (1879) proposed empirical relation based on extensive experiments for bed load transport parameter assuming that the bed material moves in a series of layers parallel to the bed, the velocity of each layer varying linearly from a maximum for the top layer on the bed surface to zero from the lowest layer at some depth.

$$\emptyset_b = A\,(\tau_o - \tau_{oc})\,\tau_o \quad (1)$$

where

$A = \gamma_s \Delta h \Delta V / 2\tau_{oc}^2$,

Δh the thickness of each layer,

ΔV is the velocity of second layer from the bottom.

Meyer-Peter and Muller (1948) proposed the relation for uniform material with different relative densities. According to them bed load sediment transport is zero when $\tau_*' = 0.047$. The quantity $(\tau_*' - 0.047)$ may be interpreted as the effective excess shear stress causing bed load transport. Thus,

$$\emptyset_b = 8\left(\tau_*' - 0.047\right)^{3/2} \quad (2)$$

Misri, et al. (1984) and Samaga et al. (1986) working at the University of Roorkee proposed a relation on the basis of the argument that the grain shear stress would be responsible for bed load movement, for sediment size ranging from 0.49 mm to 4.94 mm as

$$\emptyset_b = 4.6X10^7\,\tau_*'^{8} \quad \text{if } \tau_*' \le 0.065 \quad (3)$$

$$\emptyset_b = \frac{8.5\tau_*'^{1.8}}{\left(1+5.95X10^{-6}\tau_*'^{-4.6}\right)^{1.43}} \text{ if } \tau_*' \ge 0.065 \quad (4)$$

where,

$$\emptyset_b = \frac{q_b}{\gamma_s}\sqrt{\frac{\rho_f}{(\rho_s-\rho_f)}\left(\frac{1}{gd^3}\right)} \quad (5)$$

Einstein (1942, 50) was the first to attempt a semi theoretical solution to the problem of bed load transport. He assumed that there is no existence of any critical shear stress but sediment moves only if lift force becomes greater than submerged weight (for non uniform bed-material transport

Tele:

E-mail addresses: sumit_gandhi2001@yahoo.co.in

only) of particle. He also assumed that the probability of re-deposition of sediment particles on the stream bed is same and the step length is entirely dependent on the sediment size. According to him $\emptyset_b$ can be found out by number of calculation from the relation

$$\emptyset_b = \frac{i_B q_B}{i_b \gamma_s}\sqrt{\frac{\rho_f}{(\rho_s-\rho_f)\left(\frac{1}{gd_i^3}\right)}} \quad (6)$$

Meunier et. al (2006) has given emphasis on mean velocity of flow for bed load movement and proposed the following graphical result for the bed load per unit width. Their analysis of velocity profile measurements is carried out in highly turbulent stream flow. Use of a logarithmic pattern fails to explain velocity profile and to estimate the shear velocity of flow. Accordingly, the only velocity for sediment movement is the mean velocity. Measurement of bed load and velocity show that bed load transport is related to the mean velocity through a power law as in Fig.1.

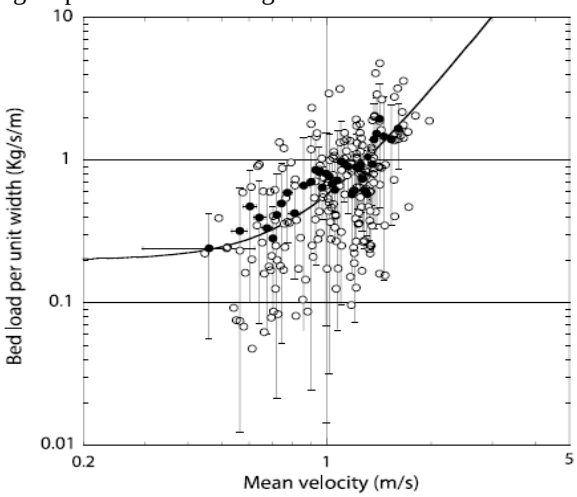

Figure 1. Variation of bed load/unit width Vs mean velocity. [Meunier et. al (2006)]

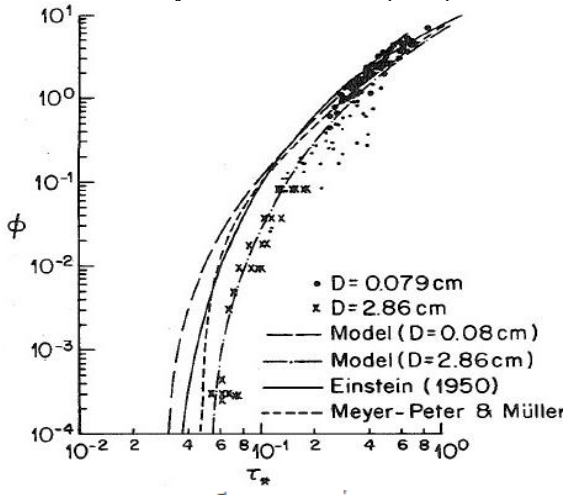

Figure 2. Variation of $\emptyset_b$ Vs and τ_*' [Patricia et. al (1989)]

Patricia et. al (1989) computes the sequences of trajectories of individual sediment grains as well as concentration of moving sediments. Parameters required to calculate bed load transport (particle velocity, bed load sediment concentration, and the height of the bed load layer) can all be determined from their model. They suggested the curve (Fig. 2) between $\emptyset_b$ and τ_*' for uniform sediments which gave relatively accurate results as compared to the other results.

Experimental Set-Up and Methodology

To evaluate the bed load transport parameter and dimensionless shear stress parameter, the experiments were carried out in a open channel. Channel was designed, fabricated and commissioned in the hydraulics engineering laboratory at JUET Guna (India).

The setup consists of a constant head tank from where the water reaches to the inlet tank through feeding pipe provided with regulating valve. Sharp edge regulating gate at the inlet is provided to prevent side wave reflection and surface undulation so that a stabilized flow is available at the inlet of main channel. Also, controlling gate at the end of channel is provided to maintain certain volume of water and sediment concentration in the main channel. Setup is made up of perspex sheet for observational purpose; parallel rails were mounted at the top of side walls for sliding of pointer gauge in order to measure depth at different positions along the length and across the width of the main channel. The channel dimension is 5 m × 0.2 m × 0.25 m.

Numbers of runs for the different values of the velocity ranging from 0.2 m/s to 0.8 m/s for different bed materials (uniform and non-uniform) were conducted. Each experiment were conducted for the half an hour. For each experiment velocity of flow, depth of flow and bed laod moved were measured. Observations were collected for the variaion of bed load per unit width (kg/m/sec) for different mean velocity of flow for uniform and non-uniform sediments. Bed load transport parameter '$\emptyset_b$' and dimensionless shear stress 'τ_*'' were then calculated from the above measurement. Results are used; to compare with Meunier (2006) and Roorkee's approach (1986) [i.e. Gilbert (1914), Pazis & Graf, Paintal (1977), Misri et. al (1984), Ranga Raju & R. J. Garde (1986)]; and to carryout empirical modeling for obtained data.

Empirical Modeling

Based on the theory of bed load transport, the important variables affecting bed load movement i.e., q_b, γ_s, γ_f, d, D, g, F_e, V, N, R, S, μ and using Buckingham π-method treating d, v and γ_f as reapting variables; following dimensionless terms were developed

$$f\left(\frac{q_b}{du}, \frac{\gamma_s}{\gamma_f}, \frac{R}{d}, \frac{gd}{u^2}, \frac{u\mu}{\gamma_f D^2}, \frac{D}{d}, S, N\right) = 0 \quad (7)$$

where,
D = sieve diameter,
d = sediment diameter,
N = Rugosity/Manning-Strickler coefficient,
q_b = fraction of bed sediment discharge of a given range,
R = hydraullic mean depth,
S = bed slope,
γ_s = unit weight of solid,
γ_f = unit weight of fluid,
μ = dynamic viscosity of water.

π-terms are developed using these dimensionless parameters and following empirical relations are developed on the basis of extensive experimental work carried out;

$\tau^{*'} = 0.186\ \emptyset_b^{\,0.2071}$ (8)

(For uniform sediment material, d = 2.36)

$\tau^{*'} = 0.1202\ \emptyset_b^{\,0.1797}$ (9)

(For non-uniform sediment material, d = 0.87 mm to 12.5 mm)

where,
$\emptyset_b$ = bed load transport parameter,
$\tau^{*'}$ = dimensionless shear stress.

Results and Discussion

Bed load

Uniform Sediment (2.36 mm)

Fig. 3 shows the bed load transport rate per unit width as a function of the mean velocity for the uniform sediments size (d = 2.36 mm). Present experimental data is compared (R^2 value 0.934) with the Roorkee's approach and Mayer-Peter's result and it is clear from the plot that experimental result follows the same pattern as given by Mayer-Peter (1948) with R^2 values 0.997 and Roorkee's approach with R^2 value 0.988 respectively. However, both shows some deviation from the present result which can be explained on the basis that present study is made for small range of sediment size were as in Roorkee's approach is made for larger range of sediment size as mentioned above.

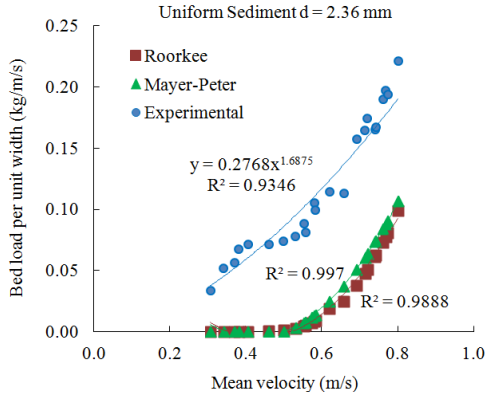

Figure 3. Bed load transport rate per unit width as a function of the average velocity U (d = 2.36mm)

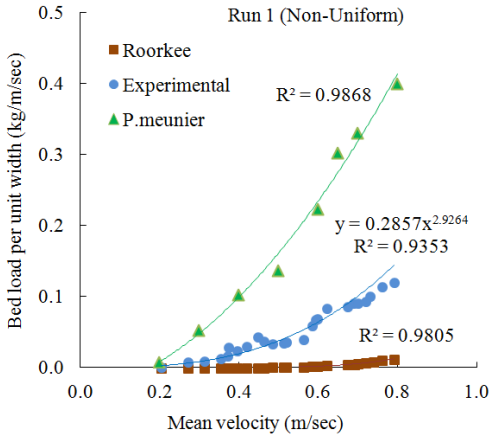

Figure 4. Bed load transport rate per unit width Vs mean velocity for non-uniform bed material (Run 1)

Non-Uniform Sediments (0.87 mm – 12.5 mm)

Fig. 4 – Fig. 6 shows a variation of bed load transport rate against the mean velocity for non-uniform sediment sizes and experimental results were compared with Meunier (2006) and Roorkee's approach (1984, 86). The variations among different plots attributed to the varying experimental conditions. Roorkee's approach (1984, 86) is based on different experimental conditions in which they varied most of the parameters like velocity, bed slope of the channel, different range of sediments sizes between 0.07 mm to 40 mm and different bed material compositions. Also, they used the flume setup having a length of 16 m, width of 0.75 m, and depth of 0.48 m. On the other hand present study have been made with constant bed slope (bed surface was made rigid); boundaries were smooth with single material composition. Bed load transport rate is calculated using Roorkee's relation (Eqn. 5) and it came out to be very low on the other hand in present experiment it's quite higher for same mean velocities.

Run 1

Fig. 4 shows a good comparison of experimental result with other authors as mentioned. R^2 values 0.935, 0.986 and 0.980 for experimental, Meunier (2006) and Roorkee's approach (1984, 86) respectively shows that variation follows same trend. However, some data scattering in the present experimental work about the fitted line which may be attributed to inaccuracy in measurement but lying within $\pm$ 20% of the suited line. Using present measured velocity and the arithmetic mean size of non-uniform bed material (varying between 0.87 mm – 12.5 mm), author calculated the bed load transport rate for Roorkee's and Meunier's approach and compared with the experimental data as seen in the plot.

Run 2

Fig. 5 shows same plot as in case of run 1 but the trend line shows slight different pattern. Bed load per unit width increases non-linearly up to a mean velocity of 0.8 m/sec in all the three cases compared. The slight change in Roorkee's pattern may be because of large variation of sediment sizes from 0.07 mm – 40 mm and 0.87 mm – 20 mm for present experiment. However, R^2 value equal to 0.939 shows good fitting of line for the experimental data in comparison with run 1. Pattern of variation are also same but data obtained for bed load transport rate for Meunier (2006) and Roorkee's approach (1984, 86) using present measured velocity and the arithmetic mean size of non-uniform bed material (size ranging between 0.07 mm – 40 mm for both Meunier and Roorkee) shows good fitting with proposed line.

Run 3

Fig. 6 shows the plot of Meunier (2006) and Roorkee's approach (1984, 86) using present measured velocity and the arithmetic mean size of non-uniform bed material (size ranging between 0.07 mm – 20 mm for both Meunier and Roorkee) along with present experimental result for non-uniform sediment sizes ranging from 0.87 mm – 12.5 mm. For this run R^2 value comes out to be 0.975, which is much better than the above two runs. For measured velocity and the arithmetic mean size of non-uniform bed material, same properties are studied and explanation is attributed to the similar reasons for varying channel conditions among all three results.

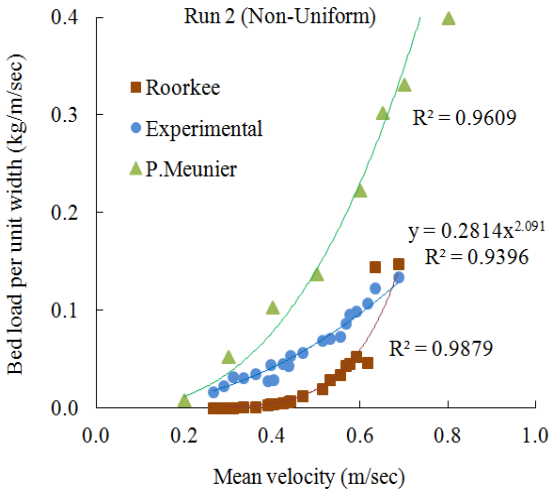

Figure 5. Bed load transport rate per unit width Vs mean velocity U for non-uniform bed material (Run 2)

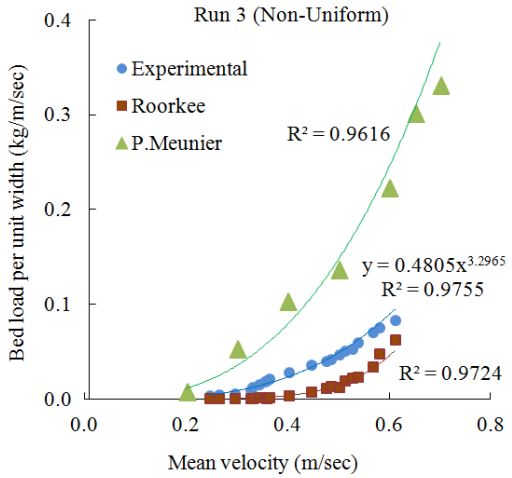

Figure 6. Bed load transport rate per unit width Vs mean velocity U for non-uniform bed material (Run 3)

Shear Stress (τ*')

Uniform Sediment (2.36 mm)

Fig. 7 shows variation of dimensionless shear stress with the bed load transport parameter for uniform sediment size of 2.36 mm for experimental data and Roorkee's data. It is clear that similar pattern is seen in both the cases. The value of R^2 = 0.920 [Eqn. (8)] shows good relation between $Ø_b$ and τ*'. It is also proved from R^2 = 0.929 for Roorkee's approach (1984, 86) that the same amount of deviation is seen from the respective fitted line.

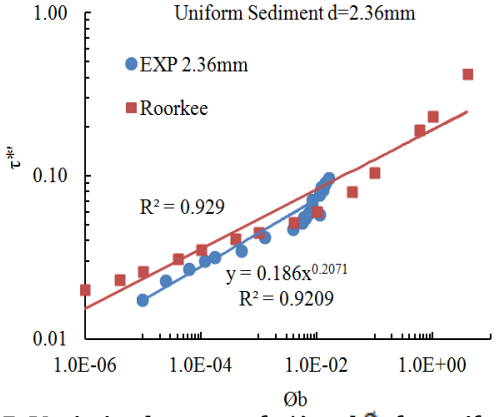

Figure 7. Variation between of τ*' and $Ø_b$ for uniform bed material

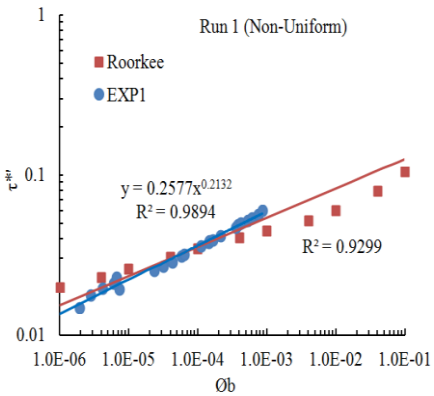

Figure 8. Variation between τ*' and $Ø_b$ for non-uniform bed material (Run 1)

Non-Uniform Sediments (0.87 mm – 12.5 mm)

Fig. 8 – Fig. 11 shows a variation of dimensionless shear stress with the bed load transport parameter for non-uniform sediment sizes. Experimental results were compared with Meunier (2006) and Roorkee's approach (1984, 86) and discussed well about the deviations and its suitability for field applicability. The variations among different plots attributed to the varying experimental conditions like velocity, boundary conditions, bed slope, sediments sizes, etc. On the other hand present study have been made with constant bed slope (bed surface was made rigid); boundaries were smooth with single and mixed sediment compositions.

Run 1

Variation of dimensionless shear stress with the bed load transport parameter is observed in Fig. 8. R^2 = 0.989 nearly equal to one indicates, the empirical relation [$τ^{*'} = 0.2577\ Ø_b^{0.2132}$] developed for the present case defines well the phenomenon and suitable for particular range of sediment size. Variation can be attributed to different sediment size variation; in present case size varies between 0.87 mm – 12.5 mm were as in case of Roorkee's approach it varies between 0.07 mm – 40 mm.

Run 2

Fig. 9 also shows similar variation of dimensionless shear stress with the bed load transport parameter. The empirical relation $τ^{*'} = 0.1027Ø_b^{0.1934}$ with R^2 = 0.91 holds good for correlating the two parameters of the present experimental phenomenon. Difference between both the plots is attributed to the varying experimental conditions and different size range of sediment used as mentioned above.

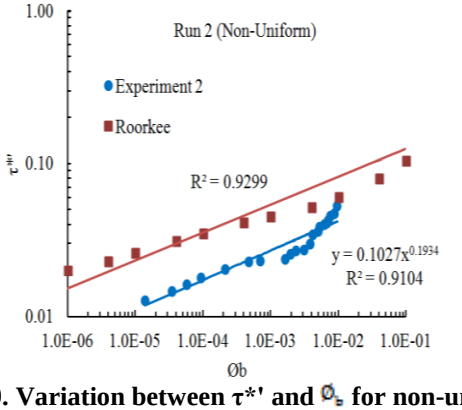

Figure 9. Variation between τ*' and $Ø_b$ for non-uniform bed material (Run 2)

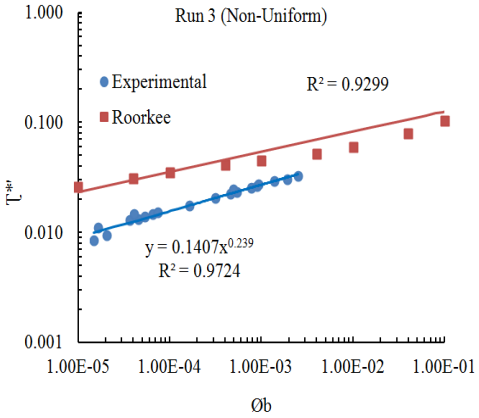

Figure 10. Variation between τ*' and $Ø_b$ for non-uniform bed material (Run 3)

Run 3

Fig. 10 shows similar variation of dimensionless shear stress with the bed load transport parameter for both experimental and Roorkee's methods. Gap between both the

plots is mainly due to the different sediment material composition and varying boundary conditions. The value of R^2 = 0.972 nearly equal to one shows regression line meets the data well and the relation proposed $\tau^{*'} = 0.1407\ \emptyset_b^{0.239}$ holds good for particular range of experimental condition. Variation can be explained on the basis of; sediment size varies between 0.87 – 12.5 mm in present case were as in case of Roorkee's approach it varies between 0.07 mm – 20 mm which different from above two runs.

An approach has been made to combine results of all three runs and correlate with the Roorkee's results in order to obtain a common empirical relation for non-uniform sediment flow. Fig. 11 shows combined representation of data and empirical relation [$\tau^{*'} = 0.1202\ \emptyset_b^{0.1797}$] for all the above three cases of non-uniform size of sediments with R^2 = 0.696. It shows the deviation of data points from the regression line and with the Roorkee's approach which is due to the small range of sediment size for present case (i.e. 0.87 mm - 12.5 mm) and large range of sediment size for Roorkke's approach (0.07 mm – 40 mm) and also due to different mean velocity of flow.

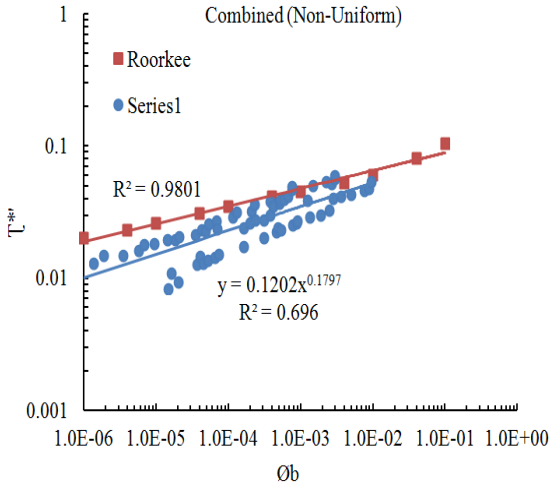

Figure 11. Variation between τ*' and $\emptyset_b$ for non-uniform bed material (Combined)

Conclusion

A good correlation for bed load transport as a function of the mean velocity for the uniform sediments size is observed with Roorkee's approach and Mayer-Peter's result. However, deviation is only because of larger range of sediment size in Roorkee's approach. In case of non-uniform sediments size were experimental results are compared with Meunier and Roorkee's approach, it can be concluded that present experimental conditions is responsible for higher bed load transport rate at particular mean velocities in comparison with the two.

Models developed [Eqn. (8) & Eqn. (9)] for shear stress in terms of bed load transport parameter through empirical modeling for uniform and non-uniform sediments defines well the phenomenon and in good agreement with Roorkee's approach (1986) [i.e. Gilbert (1914), Pazis & Graf, Paintal (1977), Misri et. al (1984), Ranga Raju & R. J. Garde (1986)] and therefore can be used for field application with confidence. It can also be applied for other boundary, flow and sediments conditions.

Acknowledgment

Authors would like to thank Hydraulics Laboratory and its staff, Department of Civil Engineering, Jaypee University of Engineering & Technology, Guna (M.P.), India to carry out the experimental work.

Nomenclature

A	=	Cross-section area
D	=	Sieve diameter
d	=	Sediment diameter
F_r	=	Froude number
i_b	=	Fraction of bed sedimet of a given range
i_B	=	Fraction of bed load of a given range
N	=	Rugosity/Manning-Strickler coefficient
Q	=	Discharge
q_b	=	Fraction of bed sediment discharge of a given range
q_B	=	Fraction of bed load discharge of a given range
R	=	Hydraullic mean depth
R^2	=	Coefficient of determination
S	=	Bed slope
γ_s	=	Unit weight of solid
γ_f	=	Unit weight of fluid
ρ_s	=	Mass density of sediment
ρ_f	=	Mass density of fluid
$\emptyset_b$	=	Bed load transport parameter
τ*'	=	Dimensionless shear stress
μ	=	Dynamic viscosity of water
τ_o	=	Shear stress
τ_{oc}	=	Critical shear stress

References

[1] Du Boys, "Le Rohene et les rivieres a lit affouillable Annales des Ponts et Chaussees", Series 5 (18), 141-195, 1879.
[2] Einstein, H. A., "Formulas for The Transportation Of Bed- Load", Trans., ASCE. 107, 561-597, 1942.
[3] Einstein, H. A., "The Bed Load Function for Sediment Transportation In Open Channel Flows", Tech. Bulletin No. 1026, U.S.D.A., Soil Conserv. Service, 1-71, 1950.
[4] Gilbert, G. K., "The transportation of de´bris by running water, U.S., Geological Survey", Prof. 86-263, 1914.
[5] Graf. W, "Hydraulics of Sediment Transport", McGraw-Hill Series In: Water Resource and Environmental Engineering, 1971.
[6] Meyer-Peter, E. and R. Muller, "Formula for Bed Load Transport", Proc. IAHR, 2nd congress Stockholm, 1948.
[7] Misri R. L., R. J. Garde and K. G. Ranga Raju, "Bed Load Transport of Coarse Non Uniform Sediment", JHD, Proc. ASCE, 110 (3), 312-328, 1984.
[8] P. Meunier, F Metivier, E Lejeunesse, "Flow pattern and sediment transport in a braided river': The ''torrent de St Pierre'', 2006.
[9] Patricia L. Wiberg1 and J. Dungan Smith2, "Model for Calculating Bed Load Transport of Sediment", Journal of Hydraulic Engineering, 115, 1, 101-123, 1989.
[10] Pazis G. C. and W. H. Graf, "Weak sediment transport", J. Hydraulic Divison, ASCE, 103, 799–802, 1977.
[11] R. J. Garde, K.G. Ranga Raju, "Mechanics of Sediment Transportation and Alluvial Stream Problems", New Delhi: New Age International, 262. ISBN 978-81-224-1270-3, 2000.
[12] Samaga B. R., K. G. Ranga Raju and R. J. Garde, "Bed Load Transport of Sediment Mixture", JHE Proc. ASCE, 112 (11), 1003-1017, 1986.