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Total Sediment Transport Rate of Alluvial Rivers for Non-Uniform Sediments: The State of Art

KEYWORDS: sediment transport, total sediment transport, macroscopic approach, microscopic approach

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ABSTRACT Sediment transport is one of the most dynamic and consistent phenomenon of nature. Water in open channels is a powerful carrier of sediments over large distances. Immense quantities of sediment of various sizes, shapes and density get carried away by different modes of movement like bed load, suspended load and wash load, depending upon the flow and channel characteristics. Rarely do we see most sediments flowing in an open channel of same size and specification. Extreme diversity of soil condition over the entire length of the river contributes in different sediment size too. The variation in extent of attrition experienced by a sediment from the beginning of its travel results in different sizes of sediments at any stage of channel. Thus we predominantly deal with non-uniform sediments in natural conditions. It is important to know the total sediment load for various engineering applications and studies, like hydraulic structures and morphological studies for flood protection, etc. There are two approaches to predict total load: Microscopic and Macroscopic. While total sediment load is calculated as sum of suspended and bed load in microscopic approach, it is directly calculated in macroscopic approach ignoring the suspended load as independent process. Both approaches have researchers suggesting some method of prediction of total sediment load for either uniform sediment or non-uniform sediments or both. Approaches for non-uniform sediment transport are discussed in the present seminar to highlight their limitations and suitability for field application.

I. INTRODUCTION

Most of the rivers or rivulets have water flowing in monsoon season only. For the remaining time of year, the flow is either very low or absent. For bed load movement considerable force of flow is required, however some suspended load consisting of smaller and lighter sediments can take place even in small flow. It would thus be more appropriate to evaluate Sediment Transport Rate for a channel separately for each period of year. However, the current practice for such rivers is to undertake sampling of bed load before monsoon, during monsoon and after monsoon, corresponding to significant changes in bed layer. Bed load is also measured for any sharp change in stage (more than 3 m) during monsoon (CWC, annual report, 2012-13). Another significant factor that has affected the natural sediment transport behavior in an open channel is construction of hydraulic structures like check dams, weirs, hydroelectric plants, etc. The knowledge and correct prediction of total sediment load carried by the channel is necessary to tackle hydraulic problems like aggradation, degradation, river training etc. Majority of relationships for total load prediction is based in flume data and the river data in which wash load is estimated and excluded from the measured total load (Garde, R. J. and Rangaraju, K. G., ed.2010). Sediment transport capacity refers to the volumetric or mass rate at which the river can transport sediment, (Chanson, 1999).

II. DIFFERENT APPROACHES OF TOTAL LOAD ANALYSIS

There are two predominant approaches for predicting total sediment load in open channels with mobile bed. The first approach is Microscopic, which subdivide the total sediment load into either suspended load and bed load or measured load and unmeasured load. Due to the limitations of sampler, some suspended load and bed load get left out. This is called unmeasured load. The second approach, i.e., Macroscopic approach, does not consider suspended load as separate entity but treat it as an extension of bed load transport as a continuous process at an advanced stage and also its theory that total sediment transport rate should be primarily related to the shear parameter and no distinctions need to be made between bed load and suspended load.

Both the approaches have some researchers who proposed different relationships, based on different concepts like total energy, shear stress, etc., for predicting the total sediment load. The various methods for predicting total sediment load are listed here as: Einstein (1950), Colby and Hembree (1955), Bagnold (1966), Hsieh W. Shen and Gary S. Hung (1983), Van Rijn (1984 a, 1984 b), Samaga et al. (1986 a, 1986 b) and Swamee and Ojha (1991) are some of the common microscopic approaches. All of these are suitable for non-uniform sediments.

Laursen (1958), Garde and Albertson (1958), Garde and Dattatri (1963), Colby (1963), Bishop, Simons and Richardson's Method(1965), Engelund and Hansen's (1967), Graf and Acaroglu (1968), The Toffaleti (1968) , Graf (1971), Shen and Hung (1972), Engelund-Hansen (1972), Ackers and White's (1973), White et al. (1973), Yang(1984), Karim and Kennedy (1990), Shu-Qing Yang and Siow-Yong Lim (2003) and S. K. Sinnakaudan et. Al (2006) are prominent macroscopic approaches. Only three approaches can be applied for non-uniform sediments.

Microscopic Approaches for finding total sediment

Einstein (1950) proposed analytical and graphical procedures for the computation of sediment discharge of sediment streams.

Einstein's Total load function in a given size range is given as

$$i_T q_T = i_b q_b + i_s q_s \quad (1)$$

$$i_T q_T = i_b q_b + i_b q_b (PI_1 + I_2) \quad (2)$$

$$i_T q_T = i_b q_b (PI_1 + I_2 + 1) \quad (3)$$

Colby and Hembree (1955) method is a modification of Einstein's method and usually goes under the name of

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Modified Einstein-Procedure. Calculations are based on the actual measurement of the velocity, its local values and averaged ones, rather than on the slope S. As in Einstein's procedure, the total load in a given size range is written as

$$\frac{i_s q_t}{i_{sm} q_{sm}} = \left(\frac{E}{A_E}\right)^{Z-1} \left(\frac{1-A_E}{1-E}\right)^2 \frac{(1+PI_1+I_2)A_E}{(PI_1+I_2)_E} \quad (4)$$

Bagnold (1966) proposed new dimensionless equations, it is defined stream power, τV as the power per unit bed area which can be used to transport sediment.The total load in dry weight per unit time and unit width is the sum of bed load and suspended load and is given in equations (5).

$$q_t = q_{bw} + q_{sw} = \frac{\gamma_s - \gamma}{\gamma} \tau V \left(\frac{e_b}{\tan\alpha} + 0.01\frac{V}{\omega}\right) \quad (5)$$

Hsieh W. Shen and Gary S. Hung(1983) developed a procedure to calculate the total sediment transport rates from the flow and suspended sediment data collected from the sampled zone (by depth integrated sampler). This procedure is a modification of the well-known "Modified Einstein Procedure."

Van Rijn (1984a,b) Van Rijn (1984 a) proposed a bed load transport capacity formula as the product of the saltation height, the particle velocity for particle diameter ranging from 0.2 mm to 2 mm, as given in equation (6) and (7).

$$q^*_b = 0.53(s-1)^{0.5} g^{0.5} d_s^{1.5} D_*^{-0.3} \tau^{2.1} \; if \; \tau < 3 \quad (6)$$

$$q^*_b = 0.1(s-1)^{0.5} g^{0.5} d_s^{1.5} D_*^{-0.3} \tau^{2.1} \; if \; \tau \geq 3 \quad (7)$$

Rijn's (1984b) expression for the estimation of suspended load is based on integration of the product of the vertical profiles of the flow velocity and sediment concentration as given below.

$$q_s = \int_a^D C_y \, u d_y \quad (8)$$

Belle R. Samaga, K. G. Ranga Raju, and R. J. Garde (1986a, b) conducted experiments on alluvial beds of four sediment mixtures having different arithmetic mean diameters and standard deviations. The bed load transport rates of individual fractions were measured. Einstein's method, Profitt and Sutherland's method and Misri's method of calculation of the bed load transport of individual fractions for sediment mixtures

$$\Phi_{bi} = 3.62x10^7(\tau'_{*i})^8 \text{ for } \tau'_{*i} \leq 0.065 \quad (9)$$

$$\Phi_{bi} = 8.5(\tau'_{*i})^{1.8}$$

$$[1 + 5.95 \times 10^{-6} 10_i \; (\tau'_{*i})^{-4.7}]^{1.45} \quad \tau'_{*i} > 0.065 \quad (10)$$

Samaga,et al. observed that, initiation of motion of a given size of sediment as well as its transport rate in open channels is complicated as these are affected by the presence of the other size sediments in the mixture.

$$\Phi_{si} = \frac{q_{si}}{\rho_s p_i d_i \sqrt{\frac{1}{\Delta g d_i}}} \quad (11)$$

Swamee and Ojha (1991) developed empirical equations for the bed-load and suspended-load transport rates of non uniform sediments essentially using the data of Samaga (1986) as given in equation (12) and (13). The non-uniformity of sediments is described by an empirical three-parameter grain-size distribution equation for unimodal shapes.

$$\Phi_{Bx} = \left\{ \left[\left(\frac{0.8}{M}\right)^{4.75} + M^{0.004}\right]^{1.75} \left[\frac{0.0871}{\tau'^{*}_{*x} M^{0.25}}\right]^9 + \left[\left(\frac{0.01}{M}\right)^{0.06} + M^{2.35}\right]^{1.2} \left[\frac{0.0339}{\tau'^{*}_{*x}{}^{9M/(8M^2+1)}}\right]^{1.6} \right\}^{-1} \quad (12)$$

$$\Phi_{Sg} = \left\{ \left[\left(\frac{0.072}{M}\right)^4 + M^{2.8}\right] \left[\frac{0.567}{\tau'^{*}_{*s} M^{0.635}}\right]^6 + \left[\left(\frac{0.177}{M}\right)^2 + M^{1.455}\right]^2 \left[\frac{0.538}{\tau'^{*}_{*s}{}^{8M/(7M^{1.425}+1)}}\right]^2 \right\}^{-1} \quad (13)$$

Wu, Wang and Jia Formula (2000) developed a correction factor to account for the hiding and exposure mechanism of non-uniform sediment transport. Based on this concept, the formulas to calculate the critical shear stress of incipient motion and the fractional bed-load and suspended load transport rates of non-uniform sediment have been established.

$$\Phi_{b,i} = P_i.0.0053 \left[\left(\frac{n'}{n}\right)^{3/2} \frac{\tau_b}{\tau_{ci}} - 1\right]^{2.2} \quad (14)$$

$$\Phi_{si} = P_i.0.0000262 \left[\left(\frac{\tau}{\tau_{ci}} - 1\right) \frac{u}{\omega_i}\right] \quad (15)$$

Macroscopic Approaches for finding total sediment

The Toffaleti (1968) developed equation from Einstein's equation and combined it with extensive field work. It consists of complex formulas that break sediment movement into four vertical zones.

$$g_{ssL} = M \frac{(R/11.24)^{1+n_v-0.786z} - (2d_{35})^{1+n_v-0.786z}}{1+n_v-0.786z} \quad 16$$

(Lower zone)

$$g_{ssM} = M \frac{(R/11.24)^{0.244z}\left[(R/2.5)^{1+n_v-z} - (R/11.24)^{1+n_v-z}\right]}{1+n_v-z}$$

(Middle zone)

(17)

$$g_{ssU} = M \frac{\left(\frac{R}{11.24}\right)^{0.244z}\left(\frac{R}{2.5}\right)^{0.5z}\left[R^{1+n_v-1.5z} - \left(\frac{R}{2.5}\right)^{1+n_v-1.5z}\right]}{1+n_v-1.5z}$$

(Upper zone)

(18)

$$g_{sb} = M\,(2d_{35})^{1+n_v-0.756z}$$

(19)

$$M = 43.2 C_z (1+n_v) V R^{0.756z-n_v}$$

(20)

$$g_s = g_{ssL} + g_{ssM} + g_{ssU} + g_{sb}$$

(21)

Ackers and White (1973) applied dimensional analysis to express mobility and sediment transport rate in terms of some dimensionless parameters. The formula is most appropriate for coarse silt to very coarse sand and is known to overestimate sediment transport rates for sediment smaller than coarse silt.

The generalized dimensionless sediment transport function is given as:

$$G_{gr} = C\left(\frac{F_{gr}}{A} - 1\right)^m \quad (22)$$

$$F_{gr} = u_*^n \text{gd}\left[\left(\frac{\gamma_s}{\gamma} -\right)\text{gd}\right]^{-1/2} \left[\frac{v}{\sqrt{32}\log(*D/d_s)}\right]^{1-n} \quad (23)$$

$$d_{gr} = d\left[\frac{g\left(\frac{\gamma_s}{\gamma} - 1\right)}{\nu^2}\right]^{1/3} \quad (24)$$

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III. POPULAR METHODS OF TOTAL LOAD ANALYSIS FOR NON-UNIFORM SEDIMENTS

White, Milli, and Crabe (1975) reviewed and compared sediment transport theories based on over 1,000 flume experiments and 260 field measurements. From comparisons it is observed (considering only total load functions) that Ackers and White's (1973) equation is the most accurate, followed by Einstein's (1950) and Toffaleti's (1969).

Yang and Molinas (1982) tested seven total-load formulas (Ackers and White 1973; Colby and Hembree 1955; Engelund and Hansen 1967; Maddock 1967; Shen and Hung 1972; Yang 1973; Yang 1979) for six river stations, bed materials of which are characterized by sand-range sediment.

Lau and Krishnappan (1985) also tested five formulas (Ackers and White 1973, Einstein 1950, Bagnold 1966, Lau and Krishnappan 1985, Yang 1976) using their laboratory sediment-discharge data.

Tatsuaki Nakato(1990) tested eleven existing, sediment-transport formulas against the field data measured at two United States Geological Survey (USGS) gauging stations along the Sacramento River in California, whose bed-material sizes are classified as those ranging from fine sand to coarse gravel. Among the formulas, the Ackers- White, Engelund-Hansen, Inglis-Lacey, Karim, Van Rijn, Toffaleti and Yang formulas are of total load.

R. L. Misri, R. J. Garde, F.and K. G. Ranga Raju(1984) observed that Einstein's bed load function does not accurately predict the transport rates of individual fractions in a mixture and this is primarily because Misri et al. correction for sheltering effect is at variance with experimental data.

Weiming Wu, Sam S.Y. Wang and Yafei Jia (2000) formulas have been tested against a wide range of laboratory and field data consisting 1859 sets of uniform bed-material load data selected from Brownlie's (1981). Comparison of the calculated and measured transport rates was done along with testing of three widely used bed-material load transport formulas developed by Engelund and Hansen (1967), Ackers and White (1973), and Yang (1973, 1984) using the same data set.

P. Van der Scheer, J.S. Ribberink and A. Blom (2002) studied behaviour of transport formulas and verification with data was also studied. Among the selected formulae, the formula of Wu et al. (2000) found to be the best formula to predict transport of non-uniform sediment.

IIV. CONCLUSIONS

1. Despite the complicated procedure and large number of correction factors adopted, the established theory of Einstein failed to produce satisfactory predictions in most of the applied cases and always over-estimated the transport rates. In particular, Einstein's procedure is not recommended for application to particles smaller than 0.15mm in diameter.
2. The Samaga et al procedure tends to under-estimate the sediment discharges, especially for fine bed material. Even for Samaga et al data, this procedure underestimated both bed and suspended load transport rates.
3. Toffaleti's procedure may not be used for predicting bed load, especially when the flow is carrying only bed load or the major part of the moving sediment is bed load. As such, Toffaleti's model is only applicable to sand transport, i.e. particles in the range of 0.065 mm to 2.0 mm which are mostly transported in suspension (Habibi, 1990).
4.The total load theory of Ackers and White produced satisfactory results, especially for the transportation of fine to medium sands. However, in application to high velocity conditions, Ackers and White's equation over-predicted the transport rates and resulted in unsatisfactory scores.
5.Yang showed that dimensionless unit stream power (DUSP) is the best parameter to be correlated with the total sediment concentration. This is probably the most valuable finding of Yang over two decades of investigation. Theoretically, DUSP contains the particle characteristics including size, shape and density, as well as the flow parameters including mean velocity and energy slope. Based on the theoretical approach of Yang and Molina, a simpler DUSP equation was suggested in which only one variable is unknown.

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