11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

REVIEW OF SELECTED METHODS OF SEDIMENT TRANSPORT ESTIMATION

Mehdi HABIBI and Muttucumaru SIVAKUMAR

Department of Civil & Mining Engineering, University of Wollongong
Locked Bag 8844, South Coast Mail Centre, NSW 2521, AUSTRALIA

ABSTRACT

Applicability of a number of new theories of computation of sediment discharge in river systems are investigated using field measurements from water and sediment transport in natural rivers. The transport models include those of Yang(sand transport, 1973; gravel transport, 1984), van Rijn(1984, bed and suspended load), Wiuff(1985, suspended load), Samaga et al(1986, bed and suspended load), Celik & Rodi(1991, suspended load), and Habibi & Sivakumar(1992, suspended load). Sediment data are collected from Sacramento river in California(Nakato, 1990) and two tidal channels in Netherlands(Voogt et al, 1991). The paper also includes a brief description of each of the theories.

NOTATION

The following symbols are used in this paper:

C_y = volumetric concentration of suspended materials at local depth y;
D = total flow depth;
d_{50} = median diameter of the bed material mixtures;
E_T = turbulent energy production rate per unit volume of the fluid at local depth y;
E_{Tsus} = turbulent energy used for suspension;
g = acceleration due to gravity;
q_s = volumetric transport rate of the suspended particles per unit width;
$q_{s,comp}$ = computed suspended sediment discharge;
$q_{s,meas}$ = measured suspended sediment discharge;
r = the ratio of the computed to measured sediment discharge;
S = water surface or energy slope;
u = local velocity in the flow direction at any distance y above the channel bed;
u_* = bed shear velocity;
V = average flow velocity;
W_G = the time rate of work of gravitational forces on suspended particles per unit volume of the fluid;
y = local flow depth measured from the channel bed;
β = a proportionality parameter;
Δ = $(\rho_s/\rho)-1$, relative density of the sediment particles minus one;
κ = Prandtl-von Karman constant;
ρ = mass density of the fluid;
ρ_s = mass density of the suspended materials;
ω = mean fall velocity of the suspended solids.

INTRODUCTION

Estimation of sediment transport capacity of rivers has been one of the most important research areas of alluvial hydraulics during the last several decades. Many theories have been appeared in the literature, each is an approximation to the truth over a limited range of hydraulic and sediment characteristics and none has gained universal acceptance. A hydraulic engineer needs to select the appropriate formula for a particular project. However, there is very little publications on performances and limitations of the existing equations. The problem is more serious for the case of recently developed methods, where there is less information in the literature.

To help the practicing engineers select the most suitable equation, the performances of six new methods of sediment discharge computation are investigated using field data from sediment transport in river systems. The data cover recently published hydraulic and sediment measurements of Nakato(1990) at two gauging stations on Sacramento river in California, and those of Voogt et al(1991) on two tidal channels in south western part of the Netherlands. The estimated sediment discharges, using each of the above-mentioned methods, have been compared with the actual measurements. The results demonstrate the predicability and drawbacks of each of the methods.

SELECTED SEDIMENT TRANSPORT THEORIES

Recently published methods which are able to calculate individually the transport rate of suspended materials are selected for this investigation. These theories are chosen because there is less information in the present literature about their applicability and performances to the river systems. The recently published papers in the literature on the comparison of sediment transport formulae (Nakato, 1990; Yang and Wan, 1991) do not include the selected equations given in this paper except for Yang's approach.

Yang's Unit Stream Power Approach

Yang(1972, 1973 and 1984) has approached the sediment transport phenomenon from the point of view of the rate of potential energy expenditure. Yang defined the unit stream power(USP), which is the product of mean flow velocity and energy slope, as the rate of expenditure of flow potential energy per unit weight of water. From analysis of a massive data bank, Yang found that USP is the best dominant variable which can be related to the sediment concentration or transport rate. Yang's investigation resulted in a set of dimensionless equations which have been used for the prediction of transport rates of sand(Yang, 1972 and 1973) and gravel(Yang, 1984). Yang(1973) also introduced a new criterion for incipient motion of sediment particles which is based on critical flow velocity rather than shear stress. In this method, Yang used the advantages of dimensional analysis to recognise the most important dimensionless groups and identified their interrelationships. The numerical values of coefficients in Yang's equations were determined through regression analysis with a wide range of data from sand and gravel transport in laboratory flumes.

van Rijn's Bed and Suspended Load Transport

Dutch engineer van Rijn(1984a) derived his bed load transport equation from the product of saltation height, representative velocity of bed load particles and concentration of sediment materials in the bed layer. van Rijn approached the estimation of suspended load through the depth integration of the product of vertical profiles of velocity and sediment concentration (van Rijn, 1984b). These equations have been tested using extensive field and laboratory data from various investigators. The theory also includes new relationships for reference height and reference concentration, equivalent roughness of Nikuradse, and grain and form roughness's.

Wiuff's Suspended Load Method

A simple formula, based on the concept of energy exchange in alluvial streams, is developed by Wiuff(1985) for the estimation of transport rates of suspended bed materials. The equation uses the idea that the rate of sediment transport is directly related to the energy dissipation of the flow. This hypothesis was initially proposed by Bagnold(1966) and later have been used by Engelund and Hansen(1967), Ackers and White(1973) and Yang(1972 and 1973). Using the experimental results of Guy et al(1966), Wiuff claimed that Bagnold's(1966) suspended load efficiency factor is not constant but varies linearly with Shields' dimensionless shear stress parameter.

Samaga et al Bed and Suspended Load Transport

Indian engineers Samaga, Ranga Raju and Garde introduced a theory for the computation of the transport rates of different size fractions of bed materials for the both cases of bed and suspended load. They conducted a set of experiments in a 30 meter long laboratory tilting flume with four different size sediment mixtures(Samaga et al, 1986a and b). The results were used for the modification of Misri et al(1984) formula on bed load transport of coarse uniform particles. The modified method was applied for the transportation of non uniform bed and suspended sediments over a wide range of pertinent parameters. Samaga et al (1986a and b) introduced a corrective multiplying factor for shear stress and identified its relationship with other effective sediment parameters. Use of this factor in conjunction with transport law for uniform bed material enables computation of the transport rates of different size fractions of sediment mixtures. The theory is complicated and uses a number of parameters to be read from several tables and graphs. The proposed computational procedures are cumbersome.

Celik and Rodi's Method of Suspended Load

One of the recent contribution to the problem of sediment transport estimation has been made by Celik and Rodi in 1991. Similar to Wiuff(1984), Celik and Rodi used the concept of turbulence energy production of the flow and its relation with concentration of suspended solids to develop a new equation. After application to actual measured suspended sediment transport data, Celik and Rodi concluded that only a part of the total shear stress which is associated with the grain roughness is effective in production of suspended load. They proposed an empirical equation for the evaluation of this effective shear stress. The final formula of suspended load transport was then calibrated using a limited number of both flume and field data and generally good results were claimed. The method is simple, dimensionally homogeneous and straightforward. It can be derived directly from Bagnold's(1966) stream power relationships for suspended load.

Habibi and Sivakumar's Theory of Suspended Load Transport

Habibi and Sivakumar concentrated their study on deriving an expression for the local suspended sediment concentration based on energy concepts. They argued that the concentration of suspended solids at any depth from the channel bed should be directly proportional to the total turbulence energy of the flow at the same level(Habibi and Sivakumar, 1992).

Based on the generally accepted principles of turbulence and fluid mechanics, the authors showed that for a turbulent flow in a straight channel, total turbulent energy production rate, E_T, per unit volume of the fluid at any depth y above the channel bed can be expressed as,

$$E_T = (\rho\, g\, u_* \,S / \kappa)\,.\,(D-y) / y \qquad (1)$$

in which the energy or water surface slope is given by S, total flow depth by D, local depth by y, mass density of the fluid by ρ, von Karman constant by κ, bed shear velocity by u_* and the acceleration of the gravity by g. On the other hand, turbulent velocity fluctuations perform work on suspended solids to prevent them from settling. This work is equivalent to the work of the gravitational forces on these particles and its rate is equal to the product of the submerged weight of suspended sediments concentration times their fall velocity.

Considering C_y as the volumetric concentration of suspended materials at level y above the channel bed and ω as their mean fall velocity, the time rate of work of gravitational forces, W_G, per unit volume of the fluid can be written as,

$$W_G = C_y\, \omega\, g\, (\rho_s - \rho) \qquad (2)$$

where ρ_s denotes the mass density of the suspended materials. The work W_G from Eq. (2) is equivalent to the turbulent energy used for keeping the particles in suspension, E_{Tsus}, i. e.

$$E_{Tsus} = W_G \qquad (3)$$

Using the general concept that the turbulent energy used for keeping the sediment particles in suspension is proportional to the total turbulent energy production of the flow, E_T, then

$$E_{Tsus} = \beta\, E_T \qquad (4)$$

in which β denotes a proportionality parameter. Substituting for E_{Tsus} and E_T from Eqs. (2) and (3), and Eq. (1), respectively, into the Eq. (4), a fundamental expression is derived for the vertical distribution of the concentration of the suspended sediments as:

$$C_y = \beta \frac{S\, u_*}{\Delta\, \kappa\, \omega} \left(\frac{D-y}{y}\right) \qquad (5)$$

in which $\Delta = (\rho_s/\rho) - 1$.

This equation is dimensionally homogeneous and expresses the volumetric concentration of suspended particles, C_y at any depth y as a function of important hydraulic parameters of flow and sediment characteristics. The expression is not valid for a very thin layer close to the bed where suspension is impossible due to the large particle sizes.

Transport rate of the suspended particles per unit of channel width, q_s, can be obtained from the depth integration of the product of local concentration, C_y and flow velocity, u as

$$q_s = \beta \frac{S\,D\,V^2}{2\,\Delta\,\omega}\left[1 + \left(\frac{u_*}{\kappa V}\right)^2\right] \qquad (6)$$

in which V denotes the average flow velocity.

In development of Eq. (6) the proportionality parameter β was assumed to be independent of local depth y and Prandtl-von Karman logarithmic velocity distribution was used for u.

Discussion about functional relationship of β, whether it is a constant or a function of other sediment flow parameters and how it can be investigated, is one of the most important part of the new development. An extensive amount of sediment transport data from laboratory flumes and natural rivers are necessary for this purpose. In this paper where the focus is on suspended load equation, β is assumed to be a constant and is equal to 2%. Similar ideas have been used by Bagnold(1966) and Celik and Rodi(1991) for the evaluation of suspended load efficiency. For computation of the fall velocity, ω, the median diameter of bed material mixtures, d_{50}, is used in the following applications.

The proposed equations are purely analytical, dimensionally homogeneous, simple and suitable for engineering application. They involve a small number of easily measurable and well-known hydraulic and sediment parameters.

APPLICABILITY OF THE SUSPENDED SEDIMENT TRANSPORT THEORIES

Four independent sets of sediment transport data from three natural channels are used to test the applicability and accuracy of the selected formulae. The data include 149 individual measurements which covers a wide range of mean flow velocities (0.52 m/s to 2.28 m/s) and sediment sizes (0.18 mm to 6.30 mm). A discrepancy ratio r is defined as the ratio of computed sediment discharges to the measured values, i.e. $r = q_{s,comp} / q_{s,meas}$. When calculated r values are closer to one, the more accurate will be the predictions.

Test Against Data From Sacramento River

Nakato(1990) published 29 sets of data from suspended sediment transport in Sacramento river, California, USA. The data were collected between 1977 to 1979 from two gauging stations along the river, one in Butte City and the other near Colusa, and cover a wide range of water discharges (142 m^3/s to 2243 m^3/s), mean flow velocities (0.52 m/s to 1.79 m/s), and sediment sizes (0.33 mm to 6.30 mm). Using the developed computer programs and water and sediment data of Nakato, the transport rates of suspended bed materials have been predicted according to the selected methods. Tables I and II show the statistical analysis and quantitative comparisons of the predicted values.

Table I Statistical analysis of the computed r values for Sacramento river at Butte City

Investigator(s)	Percent-age of r in the range 0.5~2.0	Mean value of r	Standard deviation of r
Yang (1973)	25	3.02	2.74
van Rijn (1984b)	19	4.91	6.45
Wiuff (1985)	25	2.96	4.03
Samaga et al (1986b)	25	1.06	1.12
Celik and Rodi (1991)	38	0.93	1.02
Habibi - Sivakumar (1992)	69	2.67	2.97

Table II Statistical analysis of the computed r values for Sacramento river at Colusa

Investigator(s)	Percent-age of r in the range 0.5~2.0	Mean value of r	Standard deviation of r
Yang (1973)	85	1.03	0.49
van Rijn (1984b)	69	1.39	0.91
Wiuff (1985)	85	1.08	0.55
Samaga et al (1986b)	69	0.83	0.55
Celik and Rodi (1991)	8	0.23	0.16
Habibi - Sivakumar (1992)	62	0.92	0.66

Tests Against Data From Tidal Channels in Netherlands

Recently Voogt et al.(1991) collected 120 sets of data from two tidal channels in Netherlands, namely Krammer and Scheldt Estuary tidal channels. The measurements represent transportation of fine sediments (median diameter about 0.25 mm) under high velocity (mean flow velocity up to 2.28 m/s) conditions. The materials mostly travel in suspension and the bed load component is negligible. Using this data the transport rates of suspended bed materials have been predicted for all of the selected theories. The discrepancy ratios r were then calculated. Tables III and IV show the statistical comparisons of the results.

Table III Statistical analysis of the computed r values for Krammer tidal channel

Investigator(s)	Percent-age of r in the range 0.5~2.0	Mean value of r	Standard deviation of r
Yang (1973)	95	1.16	0.40
van Rijn (1984)	88	0.74	0.24
Wiuff (1985)	0	5.91	3.13
Samaga et al (1986)	88	0.74	0.24
Celik and Rodi (1991)	8	0.31	0.11
Habibi - Sivakumar (1992)	97	1.03	0.39

Table IV Statistical analysis of the computed r values for Scheldt Estuary tidal channel

Investigator(s)	Percent-age of r in the range 0.5~2.0	Mean value of r	Standard deviation of r
Yang (1973)	77	1.95	2.28
van Rijn (1984)	75	1.62	2.15
Wiuff (1985)	0	12.48	13.87
Samaga et al (1986)	74	1.45	1.33
Celik and Rodi (1991)	33	0.78	0.83
Habibi - Sivakumar (1992)	82	1.95	1.89

DISCUSSION OF RESULTS

For Sacramento river at Butte City all of the theories except Habibi-Sivakumar's model have failed to represent an acceptable prediction of suspended transport rates specially for those data sets where the reported median diameters are larger than 2.0 mm. This is because most of these methods have defined their critical condition for suspended load transport based on median diameter, d_{50}, of the whole mixture. For normal rivers sediment particles greater than 2.0 mm in diameter can be difficult to be brought into suspension. Since the bed material mixture is non uniform and the size of a considerable proportion of particles are much less than median diameter, it may be reasonable to assume that a part of the sediments move in suspension. For these particles the median diameter is not a good parameter for the definition of incipient motion. In general sediment sizes smaller than d_{50} are better indicators for initiation of motion of suspended solids.

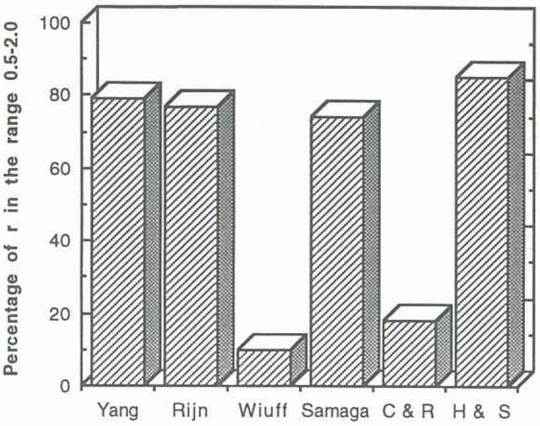

Figure 1. Average percentage of r for the whole data sets

In the other applications the four theories of Yang, van Rijn, Samaga et al and Habibi-Sivakumar have shown satisfactory predictions. For these theories respectively 79, 77, 74, and 85 percent of estimated transport rates for the whole data sets have the accuracy's within the range of 0.5-2.0 times of the measured sediment discharges (Fig. 1). However Habibi-Sivakumar theory with a score of 85% has indicated the best predicability.

Wiuff theory usually over predict the transport rates specially for the case of Netherlands tidal channels where small particles move with high velocity. This makes Wiuff's linear relation for suspended load efficiency questionable for high velocity application. In these conditions, Wiuff's expression overestimates the actual transport efficiency.

On the other hand Celik and Rodi's recently developed model always under predicts the transport rates of sediment particles. In the best estimation only 38% of estimated values are within the range of 0.5-2 times of the measured discharges(Table I). This indicates that Celik and Rodi's(1991) empirical relation for evaluation of effective shear stress for suspension underestimates the actual shear stress used in moving particles in suspension. Their proposed formula needs revision or recalibration and verification based on more data from natural rivers. In fact the predicted transport rates based on the models of Yang and Habibi and Sivakumar confirms the concept that whole part of the overall shear stress is effective in suspension rather than the part which is associated with the grain roughness's.

SUMMARY AND CONCLUSION

Five methods of estimation of sediment transport rates in river systems are briefly described. These methods have been compared with a recently developed method by the authors for the estimation of suspended sediment transport.

The selected theories were applied to 149 sets of data from three natural channels to test their applicability. Based on Habibi and Sivakumar's method about 85% of the predicted sediment discharges are within 0.5~2.0 times of the actual measurements and gives the best predicability among all the selected models. The authors' approach has shown excellent predicability specially for sediment-laden flows with high velocity and fine bed materials. Except for Sacramento river at Butte City, the estimated transport rates by the methods of Yang, van Rijn and Samaga et al are satisfactory. Wiuff's theory usually over predicts the transport rates while that of Celik and Rodi always under estimates.

Considering the wide range of variation of hydraulic and sediment parameters in different rivers and the variety of sediment transport theories, practicing engineers are recommended to look at the several methods and select the one which shows better consistency with the flow and sediment conditions and the available data.

REFERENCES

ACKERS, P. and WHITE, W. R. (1973). "Sediment Transport: New Approach and Analysis," J. Hydr. Engrg., ASCE, Vol. 99, No. HY 11, pp. 2041-2060.

BAGNOLD, R. A. (1966). "An Approach to the Sediment Transport Problem from General Physics," U.S. Geol. Survey, Prof. Paper 422-I, 37 p.

CELIK, I. and RODI, W. (1991). "Suspended Sediment Transport Capacity for Open Channel Flow," J. Hydr. Engrg., ASCE, Vol. 117, No. 2, pp. 191-204.

ENGELUND, F. and HANSEN, E. (1967). A Monograph on Sediment Transport in Alluvial Streams, Technical University of Denmark, Hydraulic Laboratory.

GUY, H. P., SIMONS, D. B. and RICHARDSON, E. V. (1966). "Summary of Alluvial Channel Data From Flume Experiments, 1956-1961," U.S. Geol. Survey, Prof. Paper 462-I.

HABIBI, M. and SIVAKUMAR, M. (1992). "New Formulation of Suspended Sediment Transport," J. Hydr. Engrg., ASCE(Submitted).

MISRI, R. L., GARDE, R. J., and RANGA RAJU, K. G. (1984). "Bed Load Transport of Coarse Non uniform Sediment," J. Hydr. Engrg., ASCE, Vol. 110, No. 3.

NAKATO, T. (1990). "Tests of Selected sediment Transport Formulas," J. Hydr. Engrg., ASCE, Vol. 116, No. 3, pp. 362-379.

RIJN, L. C. VAN (1984a). "Sediment Transport , Part I: Bed Load Transport," J. Hydr. Engrg., ASCE, Vol. 110, No. 10, pp. 1431-1456.

RIJN, L. C. VAN (1984b). "Sediment Transport , Part II: Suspended Load Transport," J. Hydr. Engrg., ASCE, Vol. 110, No. 11, pp. 1613-1641.

SAMAGA, R. B., RANGA RAJU, G. K., and GARDE, J. R. (1986a). "Bed Load Transport of Sediment Mixtures," J. Hydr. Engrg., ASCE, Vol. 112, No. 11, pp. 1003-1018.

SAMAGA, R. B., RANGA RAJU, G. K., and GARDE, J. R. (1986b). "Suspended Load Transport of Sediment Mixtures," J. Hydr. Engrg., ASCE, Vol. 112, No. 11, pp. 1019-1035.

VOOGT, L., RIJN, L. C. VAN, and DEN BERG, J. H. VAN (1991). "Sediment Transport of Fine Sands at High Velocities," J. Hydr. Engrg., ASCE, Vol. 117, No. 7, pp. 869-891.

WIUFF, R. (1985). "Transport of Suspended Materials in Open Submerged Streams," J. Hydr. Engrg., ASCE, Vol. 111, No. 5, pp. 774-792.

YANG, C. T. (1972). "Unit Stream Power and Sediment Transport," J. Hydr. Engrg., ASCE, Vol. 98, No. HY10, pp. 1805-1826.

YANG, C. T. (1973). "Incipient Motion and Sediment Transport," J. Hydr. Engrg., ASCE, Vol. 99, No. HY10, pp. 1679-1704.

YANG, C. T. (1984). "Unit Stream Power Equation for Gravel," J. Hydr. Engrg., ASCE, Vol. 110, No. 12, pp. 1783-1797.

YANG, C. T., AND WAN, S. (1991). " Comparison of Selected Bed Material Formulas," J. Hydr. Engrg., ASCE, Vol. 117, No. 8, pp. 973-989.