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BED SHEAR STRESS FOR SEDIMENT TRANSPORTATION IN THE RIVER JAMUNA

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ABSTRACT : Precisely measured velocity profile in the river Jamuna are used to determine the bed shear stress (T_0) using the logarithmic law equation (Eq. 2). This method is found to be most rational in finding the shear stress in comparison to the uniform flow equation (Eq. 1). The impact of shear stress in predicting the sediment transport has been investigated through five equilibrium formulae namely, Meyer-Peter-Muller, Bagnold, Engelund-Hansen, Ackers-White and van Rijn. The computed values, however, are found to deviate significantly from the measured values except for the van Rijn case which gives the good appreciation. The test results also focus at the seasonal variation of shear stress explaining the persistent sedimentation problem in the river Jamuna and depict the hydraulic efficiency of an alluvial river.

KEY WORDS : Bed shear, sediment transport, sedimentation problem

INTRODUCTION

The fluvial processes encountered in the alluvial rivers have long intrigued the civil engineers. Many of the commonly encountered hydraulic problems such as the transport of sediment, natural and anthropogenic changes of river morphology and other pollutants, require accurate knowledge of the hydrodynamics of a flow system associated with the physics of sediment transport. As such it emphasizes the understanding for prediction of morphological behaviour, the design of dredged sediment deposits, the design of irrigation and drainage canals, the improvement or stabilization of rivers and floodways for navigation and in flood control, the planning and design of reservoirs, the maintenance of harbour channels, beach erosion, and the control of soil erosion on watershed areas. To solve these sediment related problems, numerous empirical and semi-empirical formulae have been developed by different investigators for the prediction of bed load, suspended load, and total bed material load in alluvial channels. The first bed load equation was proposed by DuBoys in 1879. This was followed by the pioneering work of Einstein in 1942, the work of Meyer-

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Peter-Muller in 1948, the modern formulae of Bagnold in 1966, Engelund and Hansen in 1967, Yang in 1972, Ackers and White in 1973 and recent work by van Rijn in 1982. Most of these developed equations are only valid within a well defined range of parameters under certain circumstances. Therefore the application of the equations to the practical field remains limited and even in the same general conditions, a disagreement of upto 100 percent among the predictions of different empirical or semi-empirical equations may be found as not too surprising.

Precisely calculated shear stress can help significantly in determining the transport rate that is conducive to solving the aforesaid problem. This shear stress parameter has great consequences in measuring the sediment transport corresponding to natural conditions. In this regard the present study aims to determine the seasonal variation of bed shear stress in the river Jamuna based on high quality all season hydraulic data collected by the Flood Action Plan (FAP) - 24. Some conclusions have also been drawn to recognize the effects of shear stress in predicting the sediment transport using different available empirical formulae. The focus of this paper is the applicability of true shear stress on the five selected sediment transport formulas and also its implication to the river characteristics.

SITE DESCRIPTION AND DATA COLLECTION

The river Jamuna (= Lower Brahmaputra) is one of the most sediment-laden large rivers of the world and also one of the mighty rivers of Bangladesh. The detail survey and measurements were performed by FAP-24 for all months of the year 1993 except for April and May at the left channel which is located at just downstream of Bahadurabad Ghat, where the channel reach was more or less straight and the river flow is not influenced by the tide. Fig. 1 indicates the location of study area where the measurements were accomplished. The Jamuna River is a large, braiding sand-bed river which is characterised by innumerable sand bars (chars) and mid-channel islands that separate the flow into several channels with many different sizes (from hundreds of meters to kilometers wide). The number of channels is variable in space and time due to dynamic behaviour of the Jamuna River. As the left channel is considered to be the dominant one, the river section in this selected location is chosen for the study purpose.

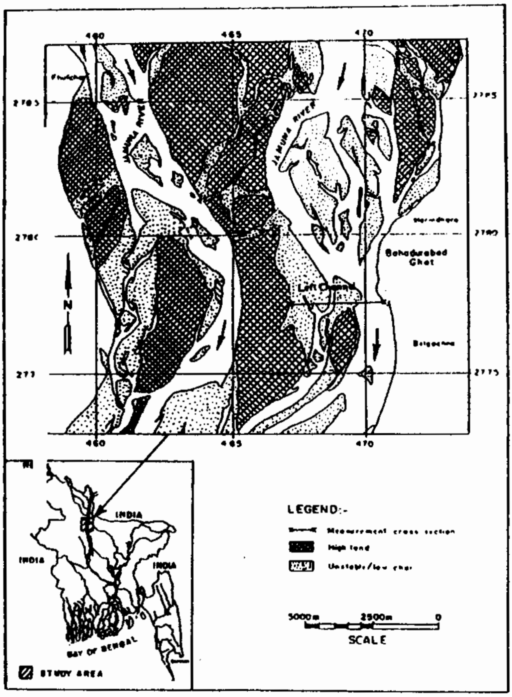

Fig 1. Site of Bahadurabad Station, the location of measurements in the Jamuna (After FAP 24, 1993)

Data used to carry out this study are velocity, discharge, cross-sectional area, energy gradient, suspended sediment concentration, bed load transport and grain size distribution. All this routine hydraulic measurements were accomplished by River Survey Project, FAP 24, Delft Hydraulics and DHI using two survey vessels. The data of velocity profile, discharge and cross-sectional area, water depth, suspended sediment concentration, bed load transport and grain size distribution were measured by using Electro Magnetic Flow Meter (EMF), Acoustic Doppler Current Profiler (ADCP), Echo Sounder, Pump Sampler, Helley-Smith Trap Sampler and van Veen Grab Sampler respectively. With the spherical electro-magnetic wave current meter (S4) three/five/six point measurements were carried out in each vertical to measure the flow velocities. Simultaneous suspended sediment concentrations. Were measured from water sediment samples using a pump system by point integrated method. Summary of hydraulic and sediment data has been given in Table 1.

Table 1. Summary of Hydraulic and Sediment Data Measurement at Bahadurabad in 1993

Month	Flow					Grain Size (μ m)				Sediment
	w	u	o	Q	WL	Bed Load		Suspended Load		Transport
	m	m	m/s	m^3/s	m PWD	D_{50}	D_{90}	D_{50}	D_{90}	kg/m/s
Jan	1368	6.40	0.77	4105	14.07	304	497	43	135	0.16-0.83
Feb	1160	5.76	0.77	3348	13.70	241	456	46	156	0.19-0.91
Mar	1304	5.56	0.63	3557	13.90	221	439	42	111	0.10-0.55
April and May : No measurements were taken.										
Jun	1386	6.94	1.42	11811	16.79	265	427	22	110	2.40-9.28
Jul	3589	9.08	1.98	34932	20.08	254	421	68	194	3.03-65.24
Aug	4609	7.87	1.58	27890	19.12	273	432	81	206	2.26-19.32
Sep	2886	8.45	1.41	27106	18.85	274	462	67	180	2.40-22.12
Oct-Nov	2516	7.40	0.97	10024	16.34	272	443	59	160	0.86-6.64
Dec	1144	8.00	1.15	4807	14.45	271	471	24	107	0.65-2.10

w, channel width; *h*, average water depth for a particular cross-section; *u*, depth-averaged flow velocity; *Q*, water discharge; *WL*, water level; D_{50}, median grain size; D_{90}, 90 percentile of grain size distribution. The bed slope *(S)* is considered as 7.7×10^{-5}.

THEORETICAL CONSIDERATION

Normally, the shear stress is estimated with the formula applicable for steady, uniform flow. Even the empirical equations for sediment transport are associated with the shear stress parameter of steady and uniform situation. The more pragmatic approach for estimating shear stress can be viewed by applying the log-law relation to the series of measured vertical velocity profile. These methods are described briefly as follows :

a) Method I - shear stress using steady, uniform flow equation, T_{O1} :

In steady, uniform flow conditions the shear stress T_{O1}, can be calculated by assuming that the friction slope equals the bottom slope, *S* and the channel is wide (*V. T. Chow*, 1973)

$$T_{O1} = pghS \tag{1}$$

where T_{01}, the bed shear stress; p, density of water; h, the water depth; S, the bottom slope; and g, acceleration due to gravity;

b) Method II - shear stress using velocity profile, T_{02} :

The widely accepted logarithmic velocity distribution was derived by Prandtl in 1942 using the mixing length theory and by von Karman in 1930 using the similarity hypothesis. It is well known that the vertical velocity distribution in rivers satisfies the "von Karan-Prandtl" equation (*Chang, 1988*) which can be written as :

$$\frac{U}{U_*} = \frac{U_m}{U_*} + \frac{23}{k} \log \left(\frac{Z}{H}\right) \qquad (2)$$

where U, point velocity at a given vertical; U_m, maximum water velocity at a given vertical; U_*, shear velocity; z, measuring depth; H, total water depth at the measuring moment; and k, universal constant of von Karman (= 0.4).

By applying this logarithmic law (Eq. 2) to the measured vertical velocity distribution, the shear velocity can be estimated with a reasonable accuracy. Taking into account the velocity profile ***U = f [log (z/H)]***, the method of least square has been used to evaluate the shear velocity, U_*. Circumstantially, this shear velocity termed as measured shear velocity has been used to compute the shear stress (T_{02}) considering the natural flow condition. The procedure to develop the shear stress (T_{02}) is described as follows. Equation (2) can be written as

$$\log \left(\frac{Z}{H}\right) = MU + N \qquad (3)$$

where, $M = \dfrac{k}{2.3\ U_*}$ and $N = \dfrac{U_m k}{2.3\ U_*}$

From the above relations one can obtain,

$$U_* = \frac{k}{2.3M} \qquad (4)$$

Therefore, shear stress, T_{02} can be written as ;

$$T_{02} = \rho \left[\frac{k}{2.3M}\right]^2 \qquad (5)$$

where M can be found by fitting the velocity profile measurements to the logarithmic form (Eq. 3) using the least square method.

DATA ANALYSIS

Grain Size Distribution : According to measurement procedures 25 litre samples were collected at the lowest suction level of Andreasen settling tube for determination of suspended sediment grain size distribution of D_{16}, D_{35}, D_{50} and D_{90}. The same grain size of bed load as collected by Helley-Smith trap sampler were analysed using conventional sieving procedures. Gradation curves for bed material at different location of Brahmaputra River are given in Fig. 2 which shows the trend of change in bed material size ranging from upstream and gradually towards downstream. The bed material of the Brahmaputra is quite uniform in size and is well sorted throughout its length. A detail analysis of bed material samples at Bahadurabad collected by van Veen grab sampler shows (Profile G) the D_{50} and D_{90} size in the range of 100-250 μm (fine sand) and 200-450 μm (fine and coarse sand) respectively. In Table-1 grain size data of bed load and suspended sediment alongwith the ranges of measured sediment transport are given.

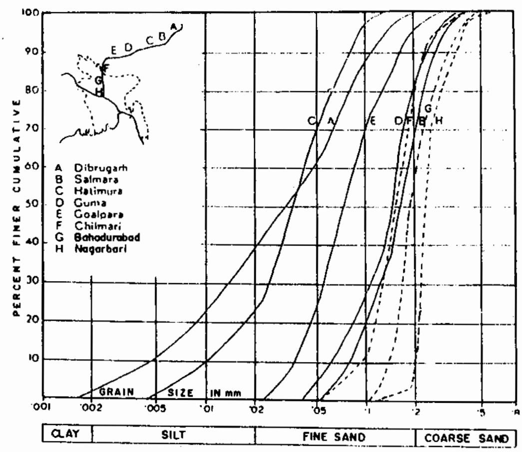

Fig 2. Grain size distribution of bed materials, Brahmaputra (after Goswami, 1983, except at G)

Representative velocity profile : The mean velocity is calculated with the use of trapezoidal rule applied on three/five/six and more point velocites. The velocity distributions for different vertical are rationalized with the help of log-law relation. A total 103 velocity distributions have been analysed through the method of least square. Inaccuracies due to this method used has been checked by the statistical parameter, 'correlation coefficient, (r)'. This parameter gives an idea of the degree of reliability between the measured data and the von Karman-Prandtl equation. Velocity distribution with correlation coefficient values greater than or equal to 0.90 are considered as representative ones. Afterwards, the flow and sediment data are reorganised in accordance with the representative velocity profile for further analysis. Fig. 3 shows a typical measured velocity profile and describes the fitting of a linear regression line between the non-dimensional parameters **(U/U_*)** and ***log (z/H)***. Out of 103 velocity profiles as analysed, 66 i.e. 64% profiles are found to have correlation greater than or equal to 0.90.

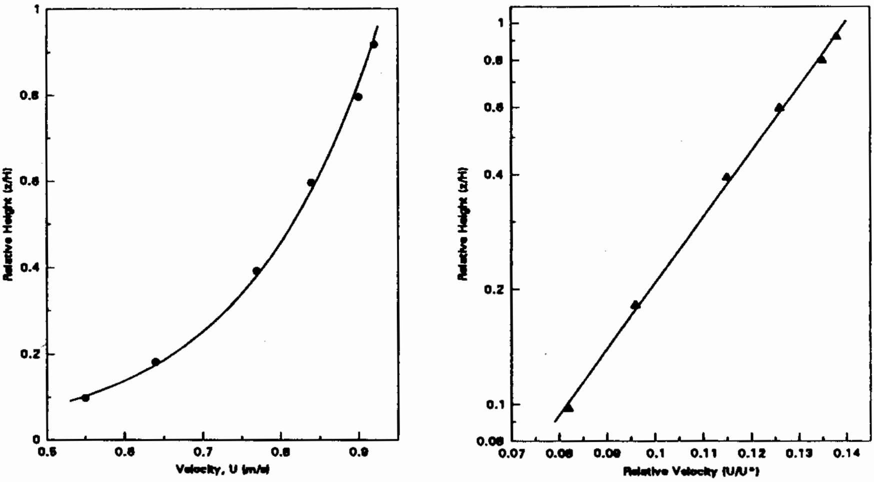

Fig 3. A typical measured velocity profile

SHEAR STRESS

Shear stress obtained by Method-II i.e. using the measured velocity is regarded as measured shear stress and contemporarily the shear stress obtained by Method-I is termed as calculated one. Monthly shear stress values, determined by both methods (Eq. 1 & 5), at Bahadurabad of river Jamuna for the year 1993 alongwith the depth averaged velocity may be seen in the Fig. 4. Following observations are made from the Fig. 4; (*i*) from January to July (i.e. in the rising part) measured shear stress varies from 6.78 N/m^2 to 59.73 N/m^2, whereas calculated shear stress varies from 5.20 N/m^2 to 7.41 N/m^2, in other words measured shear stress (Method-II) differs 23-87% from the calculated (Method-I) shear stress, (*ii*) in the falling part (i.e. July to December) the percentage of difference between the two methods is little bit higher than the rising part, (*iii*) from January to December 1993, the depth averaged velocity values ranges from 0.65 m/s to 2.0 m/s, (*iv*) the peak values of both shear stress and depth averaged velocity occurs in the month of July and (*v*) the Fig. 4 indicates that the behaviour of the depth averaged velocity is identical to that of shear stress.

It is also observed from Fig. 4 that the seasonal change in shear stress is very much moderate for the steady and uniform situation (method-I) which is totally based on speculative flow phenomena. Even, no abrupt deviation in minimum and maximum values of shear velocity (shear stress) for a particular month is observed for the method-I and seasonally this deviation occurs in more or less consistent manner. So, in order to comprehend the flow domain properly which has a great consequences on entrainment and transportation of sediment, the maximum and minimum range of shear velocity (shear stress) values derived from representative vertical velocity profile are illustrated through error bar in Fig. 5. Considering the natural circumstances, the figure 5 delineates that there is erratic seasonal change in shear velocity for method-II and usually the trend of fluctuation in minimum and maximum values of shear velocity is observed particularly in the month of July when the river flow discharge and flow velocity are higher.

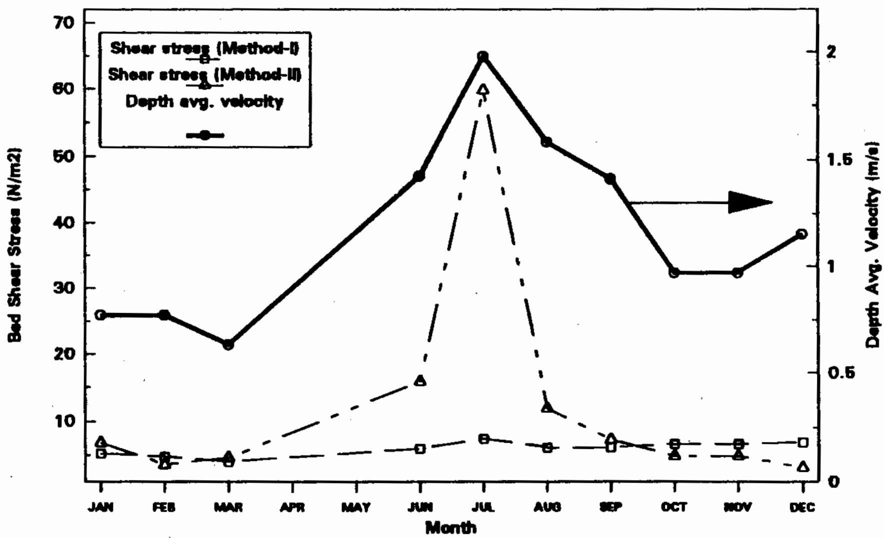

Fig 4. Temporal variation of bed shear stress and depth avg. velocity at Bahadurabad

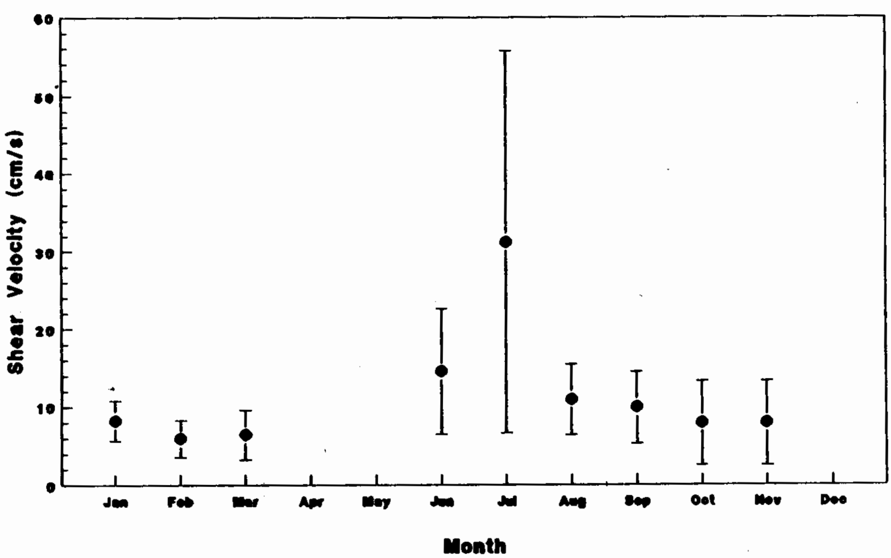

Fig 5. Fluctuation of shear velocity (Method-11) at Bahadurabad

SEDIMENT TRANSPORT

Five sediment discharge formulas, listed in Table-2, are selected in this study based on their perceived importance and corresponding to the limitations of the measurement procedure. The comparison of measured sediment transport with the empirical equation by Meyer-Peter-Miiller, Bagnold, Engelund-Hansen, Ackers-White and van Rijn using both calculated (method-I) and measured (method-II) shear stress are demonstrated in Table-2. As no measurements were taken for the month of April and May, the rate of sediment transport for the said two months has been interpolated with respect to the sediment values of preceding and following months. It is seen from the Table-2B that the Bagnold gives the abrupt predicted value in the month of July when the fluctuation of shear is very much higher than any other months. In this regard the predicted sediment transport by Bagnold is not in good compliance with the observed one. The total sediment flow at Bahadurabad in 1993 is found to be about 542 Mtons which shows good agreement with the predicted sediment flow 538 Mtons by van Rijn in case of using the measured shear stress. Applying the method-II the sediment flow predicted by Bagnold, Engelund-Hansen, Ackers-White and Meyer-Peter-Miiller are 688, 309, 231 and 26 Mtons respectively. On the otherhand applying the calculated shear stress of method-I the said empirical equations yield the predicted sediment flow as 133, 107, 93 and 6 Mtons respectively. These predicted values are much lower than the values obtained by the method-II i.e. by measured shear stress. More miraculously the Meyer-Peter-Miiller predictions are abnormally lower than the measured sediment transport rates, because of his threshold type equation and the range of sediment properties of his test was such that there was little or no suspended load, which reflects the applicability of this empirical relation to fully rough bed flow. This effect of the threshold type of predictive equation is especially troublesome when bedforms are present. Last but not the least, the improvement in the predictive values are found through the use of measured shear stress as 42, 81, 66, 60 and 75 percent in the case of van Rijn, Bagnold, Engelund-Hansen, Ackers-White and Meyer-Peter-Miiller respectively.

Table 2. Summary of Measured and Computed Sediment Transport for River Jamuna at Bahadurabad

Table 2A. Prediction of Sediment Transport by Using Method-1

Month	Sediment Transport (kg/m/s)					
	Observed	Using Empirical Equation of				
		van Rijn	Bagnold	Engelund - Hansen	Ackers-White	Meyer-Peter-Muller
JAN	0.604	0.309	0.652	0.363	0.172	0.083
FEB	0.525	0.342	0.624	0.457	0.310	0.070
MAR	0.360	0.268	0.572	0.473	0.287	0.068
APR	2.272	1.187	0.905	0.928	0.780	0.075
MAY	4.183	2.106	1.239	1.383	1.273	0.083
JUN	6.095	3.025	1.572	1.838	1.766	0.091
JUL	28.250	14.686	4.562	4.175	4.335	0.141
AUG	9.775	6.483	2.105	1.557	1.330	0.111
SEP	8.265	6.633	3.268	3.351	2.582	0.129
OCT	2.611	0.975	1.108	0.632	0.351	0.101
NOV	2.611	0.975	1.108	0.632	0.351	0.101
DEC	1.008	1.324	1.432	0.926	0.615	0.117
Total Sediment Volume in Mtons	541.65	313.81	132.89	106.60	92.87	6.46

Table 2B. Prediction of Sediment Transport by Using Method-II

Month	Sediment Transport (kg/m/s)					
	Observed	Using Empirical Equation of				
		van Rijn	Bagnold	Engelund - Hansen	Ackers-White	Meyer-Peter-Muller
JAN	0.604	0.371	0.909	0.678	0.398	0.133
FEB	0.525	0.254	0.456	0.333	0.178	0.041
MAR	0.360	0.280	0.671	0.476	0.334	0.068
APR	2.272	1.963	1.817	1.851	1.394	0.176
MAY	4.183	3.645	2.962	3.227	2.455	0.284
JUN	6.095	5.328	4.108	4.602	3.515	0.391
JUL	28.250	30.520	55.257	22.230	15.988	1.885
AUG	9.775	10.488	5.491	2.894	2.163	0.299
SEP	8.265	7.590	4.664	4.148	4.111	0.137
OCT	2.611	1.043	1.025	0.417	0.209	0.050
NOV	2.611	1.043	1.025	0.417	0.209	0.050
DEC	1.008	0.808	0.649	0.556	0.665	0.039
Total Sediment Volume in Mtons	541.65	538.13	688.24	309.39	230.74	25.87

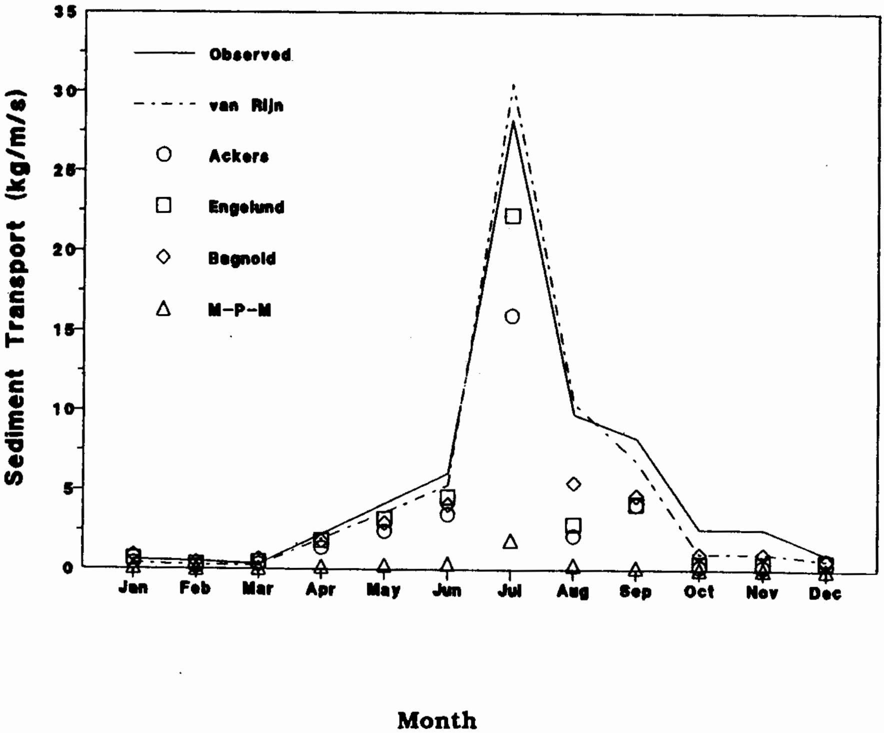

Fig 6. Comparison of sediment transport between measured and predicted Values

Considering the natural circumstances i.e. using the velocity profile, the validity of each of the selected empirical relations with respect to the observations at Jamuna is shown in Fig. 6. More importantly, the rate of sediment transport predictions (in kg/m/s) obtained with the van Rijn functions are remarkably close than any other predictions to the observed sediment transport. The following reasons can be cited to the fact. *(i)* The van Rijn function produces best result at velocities higher than 1 m/s, *(ii)* it consists of a number of separate functions which can be individually adapted according to different conditions, *(iii)* this formula is considered to be a reliable predictor in flows with bed material in size range of 100-500 μm and *(iv)* this function provides the detail analysis of flow and sediment concentration profile for individual vertical of a particular cross-section giving the result in a reliable way.

CONCLUSIONS

Extensive flow and sediment data at Bahadurabad site of river Jamuna are used to compare the accuracy of the total bed material load equations with the help calculated and measured shear stress. The effect of shear stress on sediment transport is also studied. These studies reach the following conclusions :

(1) The shear stress has great importance in predicting sediment transport and erosion in rivers. With the increase of shear stress the sediment transport increases which influences the morphological changes of rivers. From June to August the shear stress is higher ranging 11.8-59.7 N/m^2 which reflects the high suspended load carried by river Jamuna during this period. For other months the total sediment transport may be comprised of mostly bed material load and partly suspended load. During monsoon the shear stress is abruptly higher as illustrated in the Fig. 4 while the discharge and the flow velocity are also high which supports the maximum sediment transport in the river Jamuna during this period. Ultimately, this heavy sediment transport during this period causes the rivers to be extremely unstable, and the channels are constantly migrating laterally. As a consequence it reduces the hydraulic efficiency of the river and creates the navigational problem.

(2) As noticed from the Table-2A, the sediment transports by different empirical relations using the calculated shear stress are not yielding the realistic values with respect to measured ones. So, after making the measured shear stress substitution in the empirical equations, considerable improvement in the predicted values are done as demonstrated in Table-2B. This outcome reflects that the shear stress is very much susceptible parameter to sediment transport predictions.

(3) The van Rijn function contributes the good prediction for the river Jamuna than other predictors as the sediment transport rates computed by van Rijn function are in reasonable agreement with the observed values while Bagnold, Engelund-Hansen, Ackers-White and Meyer-Peter-Muller formulae give inconsistent results (Fig. 6 and Table-2). So, the van Rijn function might be useful for most engineering purposes.

(4) The calculated results from different equations also differ drastically from each other in both cases (method-I & II) i.e. the predictions do not agree with one another .

(5) Bed load equation of the threshold type, like the Meyer-Peter-Muller equation, is not useful for the sand-bed river.

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