

DEVELOPMENT OF THE BED LOAD TRANSPORT EQUATION FOR NONUNIFORM SEDIMENT IN MOUNTAIN RIVERS

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ABSTRACT

Developing a bed load transport for size fractions requires an understanding of basic theory for the proper selection of independent variables. To evaluate the selected independent variables as predictors of bed load transport equation, a linear regression procedure was initially chosen.

Development of the equation for bed load transport by size fraction in this study was based on element of three equations of bed load transport. The first is the Schoklitsch (1962) total bed load transport equation, which uses only one single size diameter D_{40} and neglects the proportion of bed load and bed material in each size fraction, but involves channel slope. The second equation is the bed load transport equation of Shih and Komar (1990) in which the proportion of bed load in each size fraction is used to obtain the bed load transport for each size fraction. The effect of the bed load size distribution is considered, but the effect of the bed material size distribution and channel slope are neglected. The third equation is the bed load transport equation of Wilcock and Southard (1989) in which both proportions of size fraction, in the bed load and in the bed material are used to calculate the bed load transport by size fraction. However, the equation of Wilcock and Southard was based on laboratory data where the size distribution of the bed load was similar to the size distribution of the bed material. It therefore needs to be compared with data from natural rivers where the bed load size distribution generally narrower than the bed material size distribution.

General relationships of the bed load transport for individual size fractions as well as total bed load transport have been developed. The approach of the relationships is the water discharge approach, which may be more appropriate for steep channels with coarse non-uniform materials characteristic of mountain regions, than one based on shear stress. Three parameters have been considered (channel slope, bed material and bed load size distribution) involve together in the equations. This basis may not be found in the previous equations for bed load transport.

Independent tests the observed data for bed load transport for individual size fractions are in a good agreement with the values obtained by derived equation, which provides encouraging support for the relationship.

INTRODUCTION

The key to understanding fractional transport rates is to determine how the size of each fraction relative to the size of the others in the mixture, affects the transport of the fraction. The intuitive argument for the variation in transport rates with grain size in a mixture is based on the relative grain size of the individual fractions. One might expect that relatively fine fractions in a mixture, being partially hidden from the flow by larger grains, would experience a smaller driving force than as if they were present in a bed of grains all of the same size. In addition, once these smaller grains are in motion, the bed over which they move is rough compared with a bed of uniform sediment. Both of these factors should diminish the transport rate of the finer fractions relative to the uniform case. On the other hand, the relatively coarse fractions might be expected to have transport rates that are greater than in a uniform bed for a given set of condition.

Natural sediments being invariably non-uniform, the transport rate of any fraction in such non-uniform material is strongly affected by the presence of other fractions. The size distribution of the transported material is invariably found to be different from the composition of bed material, particularly for low values of shear stress. This is mainly because the applied shear is not sufficient to transport all the sizes constituting the bed material. Even if all the sizes including the coarsest one are in motion, the size distributions of the transported material are not identical with the composition of the bed material.

LITERATURE REVIEW

1. Initiation of Bed Load Transport

Several studies have shown, that the stability of a particle is affected by the position of its size within the overall size distribution, given relative to a reference size (Egiazaroff, 1965; White and Day, 1982; Bathurst, 1987). Particles of the reference size are unaffected by the hiding/exposure effect and behave as if in a bed of uniform material. Empirically, the reference size is of the order of D_{50} , that size of particle median axis for which 50% of the particles are finer (Cecen and Bayazit, 1973; Proffitt and Sutherland, 1983; Bathurst, 1987).

The most familiar model for initiation of motion is the Shields (1936) relationship, which has achieved considerable success with uniform and fine sediments; its application to non-uniform gravel has proved more difficult. Variations in the measured value of the constant have also been noted for steep, rough channels. Further observations by Schoklitsch (1962) indicate that in natural rivers, where the critical conditions for sediment transport are often exceeded in only part of the channel, the use of depth as a criterion for initiation of movement is inappropriate. Schoklitsch therefore recommended that unit water discharge be used instead. This study therefore examines the available means of allowing for the effects of gravel and boulder-bed channels.

Bathurst et al (1987), using flume data for bed materials with relatively uniform size distribution, developed the empirical relationship

$$q_c^* = \frac{q_c}{g^{1/2} D^{3/2}} = 0,15 S^{-1,12} \dots\dots\dots (1)$$

where,

q_c = critical unit water discharge;

S = slope.

This applies to essentially uniform sediments for the range of slope $0,25 \leq S\% \leq 20$ and particle size $3 \leq D \text{ (mm)} \leq 44$ and for ratios of depth to particle size as low as 1.

Bathurst et al (1987) also developed a relationship for non-uniform beds using data from flume and rivers with gravel or boulder beds and slopes in the range 0,1 to 10 percent, and found empirically that, for the bed as a whole

$$q_c^* = \frac{q_c}{g^{1/2} D_{16}^{3/2}} = 0,21 S^{-1,12} \dots\dots\dots (2)$$

where D_{16} rather than the more convenient D_{50} was found to necessary to allow for the non-uniform size distribution of the bed sediment and agrees with observations (Carling, 1983) that initiation of transport in boulder-bed channels is associated with the finer fractions of the size distribution. Eqn. (2) was derived from flume data with slopes up to 9% and from river data with sediment sizes up to $D_{50} = 260$ mm and $D_{16} = 130$ mm.

The critical conditions predicted by eqn (2) do not necessarily apply to all fractions of the size distribution where the distribution is wide. In other words it predicts the first movement of bed load but this may consist of the smaller particles (sand and fine gravel) while the larger material (coarse gravel, cobbles and boulders) is still stationary. In order to predict the initiation of motion for each size fraction, eqn. (1) should be applied separately to each size fraction, taking due account of hiding and exposure effects.

In the later study Bathurst (1987) described a method which accounts for this hiding/exposure effect and predicted the critical unit water discharge for each particle size in steep, boulder-bed streams by adopting a non-dimensional form similar to equations of Andrews (1983) and Andrews and Erman (1986),

$$q_{ci} = q_{cr} (D_i / D_r)^b \dots\dots\dots (3)$$

where,

q_{ci} = the critical unit discharge for movement of particles of size D_i ;

q_{cr} = the critical unit discharge for the reference particle size D_r which is unaffected by hiding/exposure effect and can be obtain from eqn. (7);

b = exponent tentatively expressed on the basis of limited data as

$$b = 1.5 (D_{84} / D_{16})^{-1} \dots\dots\dots (4)$$

Following the approach of eqn. (4), Inpasihardjo (1991) using rivers data for bed materials with non-uniform size distribution, developed the relationship by involving the affects of river slope

$$b = 1.5 (D_{84} / D_{16})^{-25,4S} \dots\dots\dots (5)$$

2. Bed Load Transport

Gravel-bed streams possess a surface bed layer that is considerably coarser than the subsurface material, while sand-bed streams are characterized by uniformity of material in the vertical direction. Another difference between gravel- and sand-bed streams is the display of a much wider range of grain size by gravel streams. Thus, the choice of a single particle diameter to describe the mobility of the bed mixture, commonly made for sand-bed streams, might not be appropriate for gravel-bed streams. These distinct features indicate that gravel-bed streams deserve separate scrutiny.

Parker et al (1982), analysed bed load data collected by Milhous (1973) from Oak Creek, Oregon, and concluded that for poorly graded gravels, only one grain size, e.g. subpavement D_{50} is required in order to characterize total bed load as a function of Shields stress. Not much extra accuracy can be gained by calculating the bed load for each size range separately and summing can gain not much extra accuracy. Andrews (1983) used bed load data from three gravel-bed rivers to provide evidence of approximately equal mobility for most of the grain sizes at threshold conditions. The work by Parker et al (1982), Parker and Klingeman (1982), Andrews (1983), and Andrews and Parker (1985), has established a much-needed basis for describing phenomena associated with gravel-bed streams in which bed activation is a frequent event. However, their approach constitutes only a first-order approximation of reality. Diplas (1987) has established a more detailed approximation by reanalysing the Oak Creek data, by incorporating the grading effects of the poorly sorted material, neglected before, in the analysis. In later analysis Wilcock (1987) found that the approximation of Diplas (1987) is not general, but specific to the Oak Creek data. The most recent analysis by Shih and Komar (1990) for the Oak Creek data was carried out. They found that the bed material and bed load size distributions follow the Rosin distribution. Also they found that the bed load samples systematically change form log-normal (Gaussian) distributions at low flow to Rosin distributions at high discharges and bed stresses. Therefore, they proposed a relationship of bed load transport based on the bed load size distribution and unit water discharge.

GENERAL APPROACH

The present study of bed load transport builds on previous work through the extension of the existing database with the aim of developing a method of predicting the bed load transport for each size fraction in the mixture in steep, gravel/boulder-bed streams. Developing a bed load transport for size fractions required an understanding of basic theory for the properselection of independent variables. To evaluate the selected independent variables as predictors of bed load transport equation, a linear regression

Development of the equation for bed load transport by size fraction in this study was based on element of three equations of bed load transport. The first is the Schoklitsch (1962) total bed load transport equation (eqn. 6) that uses only one single size diameter D_{40} and neglects the proportion of bed load and bed material in each size fraction, but involves channel slope

$$q_{sb} = \frac{2,5}{\rho_s / \rho} S^{3/2} (q - q_c) \dots\dots\dots (6)$$

where q_c is given by eqn. (1) and the units is SI. This was originally applied by Schoklitsch to rivers with coarse sediments. The second equation is the bed load transport equation of Shih and Komar (1990) (eqn. 7) in which the proportion of bed load in each size fraction is used to obtain the bed load transport for each size fraction

$$q_{si}(D_i, \tau) = q_s(\tau) f(D_i, \tau) \dots\dots\dots (7)$$

where q_s are total unit bed load transport and $f(D_i, \tau)$ is the frequency curve for the Rosin distribution. The effect of the bed load size distribution is considered, but the effect of the bed material size distribution and channel slope are neglected. The third equation is the bed load transport equation of Wilcock and Southard (1989) (eqn. 8) in which both proportions of size fraction, in the bed load and in the bed material are used to calculate the bed load transport by size fraction

$$q_{bi} = (P_i/f_i) q_b \dots\dots\dots (8)$$

where,

- q_{bi} = the fractional transport rate for size fraction i ;
- q_b = the total transport rate;
- P_i = proportion of each fraction in transport;
- f_i = proportion of each fraction in the bulk bed sediment mixture.

However, the equation of Wilcock and Southard was based on laboratory data where the size distribution of the bed load was similar to the size distribution of the bed material. It therefore needs to be compared with data from natural rivers where the bed load size distribution generally narrower than the bed material size distribution.

Based on the three equations above and the information given by regression analysis with the data available, and taking into account also dimensional consideration the following relationship is proposed

$$q_{bi} = A(q - q_{ci}) \dots\dots\dots (9)$$

Where,

- q_{bi} = unit bed load discharge for size fraction i ;
- q = unit water discharge;
- q_{ci} = critical unit water discharge for size fraction i , calculated by eqns. (1), (3), and (5)

DATA PREPARATION

The data necessary for quantifying eqn. (9) are pair of bed load discharge for each size fraction q_{bi} and the excess unit water discharge $(q - q_{ci})$ associated with the transport rate of that size fraction. These pairs could be formed from the unit bed load discharge for each size fraction, which can be obtain from size distribution analysis of the samples, and unit water discharge recorded at the time of sampling. The data of the Roaring River (upstream and down stream sites, 1985; upstream site, 1984) (Bathurst et al, 1987; Bathurst, personal communication; Newson, personal communication) were used for developing the equation for bed load transport by size fraction, while data collected from the Pitzbach (Inpasihardjo, 1991) and from the downstream site at the Roaring River, 1984 (Bathurst et al, 1987; Bathurst, personal communication; Newson, personal communication) were used for testing the derived equation. In each case the unit water discharge was obtained by dividing the total discharge by channel width. The above strategy was used because there are variations of channel slope at three sets of the Roaring River data as well as variations in size distribution of the bed material. These conditions provide a good range of data for developing the proposed equation (eqn. (9)).

DATA ANALYSIS

The relationships between bed load discharge for each size fraction q_{bi} and the excess unit water discharge $(q - q_{ci})$ are analized with q_{ci} determined by eqns.(1), (3) and (5). Generally, q_{bi} and $(q - q_{ci})$ increase together. Eqn. (9) was therefore fitted to the data for each size fraction using regression analysis. The parameters are shown in Table1. The table shows that the relationship between unit bed load transport by size fraction and excess unit water discharge is not very good; therefore an alternative approach is required.

However, there is a relationship between coefficient A and size fraction. Figure 1 shows the relationship follows the size distribution of the bed material. It has been found by many researchers that the effect of relative grain size is stronger than absolut grain size (Wilcock, 1987; Wilcock and Southard, 1989; and Ashworth and Ferguson, 1989). Therefore it was considered that the coefficient is a function of the proportion of the bed load in each size fraction (Wilcock and Southard, 1989; Shih and Komar, 1990). Following the equation of Shih and Komar (Eqn. (7)), eqn. (9) is written as

Table -1. Parameters of Equation $q_{bi} = A (q - q_{ci})$. Fitted for the Roaring River (Upstream Site, 1985) Data for Each Size Fraction

Size Fraction (mm)	Equation Parameter A	Correlation r^2
(1)	(2)	(3)
22,40 - 45,00	2,763	0,27
11,40 - 22,40	12,520	0,36
5,60 - 11,20	2,010	0,14
2,80 - 5,60	5,840	0,30
1,40 - 2,80	15,640	0,56
0,71 - 1,40	20,830	0,65
0,355 - 0,71	9,240	0,64
PAN - 0,355	1,92	0,40

$$q_{bi} = f_{bli} B (q - q_{ci}) \dots \dots \dots (10)$$

where,

$B (q - q_{ci})$ = total unit bed load discharge;

B = a coefficient and is function of (f_{bmi}, S)

Based on eqn. (10), therefore, to achieve the improvement of eqn. (9), the relationship between total bed load transport and excess unit water discharge based on the critical unit water discharge for each size fraction for each size are obtained. The results from the linear regression analyses for each site are presented in Table - 2. and refer to the relationship

$$q_b = B (q - q_{ci}) \dots \dots \dots (11)$$

where,

q_b = total unit bed load discharge;

q = unit water discharge;

q_{ci} = critical unit water discharge for size fraction i ;

B = coefficient (non-dimensional) is function of (f_{bmi}, S) ;

f_{bmi} = proportion of the bed material in size fraction i and S = slope.

Table -2. Results of The Correlation and Regression Analyses for The Relationships Between Total Bed Load Discharge and Excess Unit Water Discharges for The Three Roaring River Data Sets

Site	Size Fraction	Equation Parameter B	Correlation r^2
(1)	(2)	(3)	(4)
Upstream Site 18/5 - 6/6, 1985 Slope S = 0,036	11,20 - 22,40	170,09	0,81
	5,60 - 11,20	114,11	0,60
	2,80 - 5,60	78,23	0,58
	1,40 - 2,80	62,74	0,60
	0,71 - 1,40	54,70	0,65
	0,355 - 0,71	49,64	0,64
	PAN - 0,355	44,98	0,62
Downstream Site 18/5 - 27/5, 1985 Slope S = 0,0523	11,20 - 22,40	1240,53	0,81
	5,60 - 11,20	577,93	0,93
	2,80 - 5,60	379,32	0,85
	1,40 - 2,80	284,67	0,83
	0,71 - 1,40	119,88	0,75
	0,355 - 0,71	195,01	0,67
	PAN - 0,355	161,06	0,60
Upstream Site 14/6 - 11/7, 1984 Slope S = 0,0383	11,20 - 22,40	66,10	0,38
	5,60 - 11,20	46,63	0,60
	2,80 - 5,60	36,85	0,56
	1,40 - 2,80	31,52	0,53
	0,71 - 1,40	28,60	0,50
	0,355 - 0,71	26,15	0,48
	PAN - 0,355	25,20	0,47

Table - 2 shows for the Roaring River data for the year 1985, the coefficient B for the downstream site for each size fraction is bigger than the coefficient B for the upstream site. The different channel slopes of the sites probably cause this. Reference to Schoklitsch (1962) shows that there is power relationship between total bed loads and slope. Therefore, the relationship between coefficient B for each size fraction and slopes are plotted in Fig. 2. A logarithmic (base e) transformation of both coefficient B and slope was performed prior to correlation and regression analyses. The results are presented in Table - 3 and refer to the relationship

$$B = C S^d \dots \dots \dots (12)$$

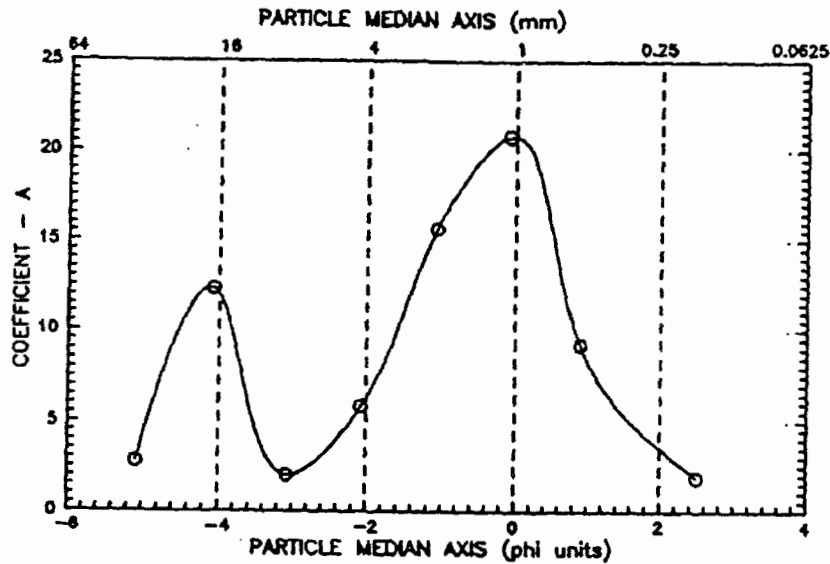


Fig. 1. Relationship Between Coefficient A of Eqn. $q_{bi} = A(q - q_{ci})$ and Size Fraction of The Bed Material for Roaring River Upstream Gauging Site, 1985

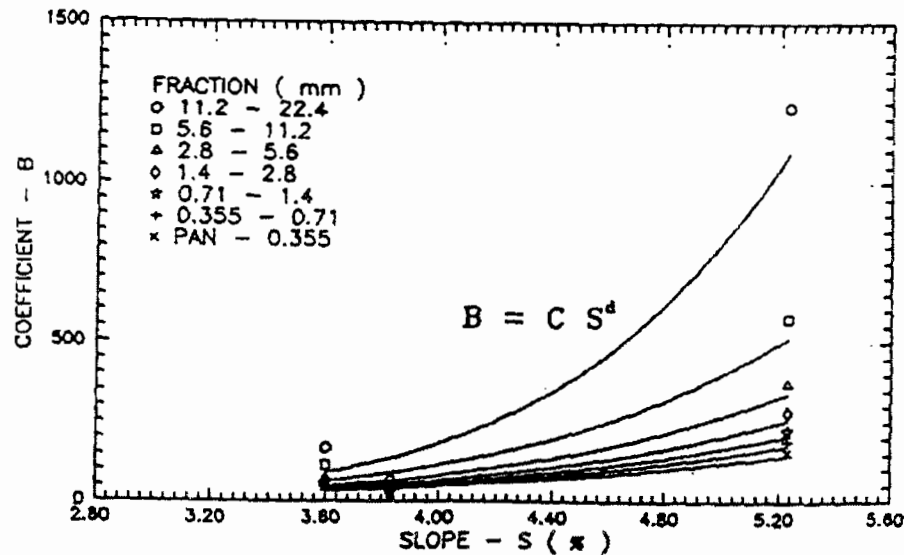


Fig. 2. Relationships Between Coefficient B of Eqn. $q_b = B(a - a_i)$ and Slope for Each

Table-3. Parameters of Eqn. $B = C S^d$ for Each Size Fraction for the Three Roaring River Data Sets.

Size Fraction (mm)	Equation Parameter		Equation r^2
	C	d	
(1)	(2)	(3)	(4)
11,20 - 22,40	0,018	6,64	0,79
5,60 - 11,20	0,053	5,55	0,76
2,80 - 5,60	0,055	5,28	0,79
1,40 - 2,80	0,064	5,02	0,80
0,71 - 1,40	0,080	4,76	0,80
0,355 - 0,71	0,094	4,56	0,79
PAN - 0,355	0,135	4,24	0,80

It can be seen from Table - 3 that the values of coefficient C and exponent d both vary with size fraction. Fig. 3 shows the relationship between coefficient C and size fraction, and Fig. 4 shows the relationship between exponent d and size fraction. Both figures show a correlation with size fraction. Again, because of the consideration that the effect of relative grain size is stronger than absolute grain size, it was decided that the two parameters depend more on the proportion of the bed material in each size fraction rather than on each size fraction itself.

From the above discussion, the coefficient B (eqn. (12)) becomes

$$B = f(f_{bmi}, S) \dots \dots \dots (13)$$

In all the analysis of the bed load, the unit for q_b in eqn. (11) was $\times 10^{-7} \text{ m}^3/\text{s}/\text{m}$, therefore, the values of coefficient B which were calculated by eqn. (12), were multiplied by 10^{-7} to obtain the unit of q_b in eqn. (11) as $\text{m}^3/\text{s}/\text{m}$. The values of coefficient B were then used to plot the relationship in Figs. 5 and 6. Fig. 5 shows the relationship between the coefficient B, Slope S and proportion of the bed material in each size fraction f_{bmi} and Fig. 6 shows the relationship between the coefficient B, slope S and relative grain size ratio D_i/D_r . The values of f_{bmi} for each size fraction for the Roaring River were calculated by the standard normal distribution (Gauss distribution), while for the bed material size distribution, which is closer to the Rosin distribution the proportion of the bed load in size fraction can be calculated using equation Shih and Komar (1990).

It is clear from Figs. 5 and 6 that, for constant proportion of bed material in each size fraction, generally the bigger the slope, the bigger is the value of coefficient B and vice versa. Therefore, Figs. 5 and 6 mathematically were expanded by linear interpolation and extrapolation for various slopes to obtain the relationship for the three parameters (B, S and f_{bmi} , or D_i/D_r). The results are plotted in Figs. 7 and 8, which can be used to obtained the coefficient B of eqn. (11). It should be noted that the lines in Figs. 7 and 8 for the slopes $S < 0,036$ were obtained to verify the mathematics of the equation, but they extrapolate beyond the range of the field data, so should not be used

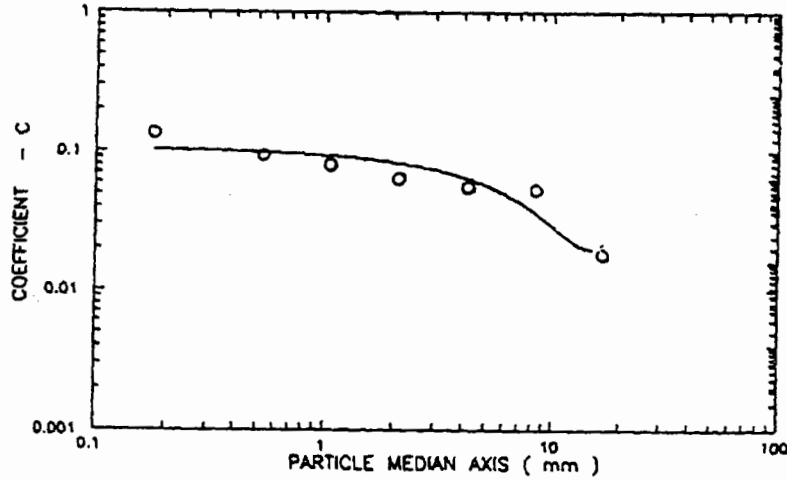


Fig. 3 Relationship Between Coefficient C of Eqn. $B = C S^d$ and Size Fractions of the Bed Load Material for the Three Roaring River Data Sets

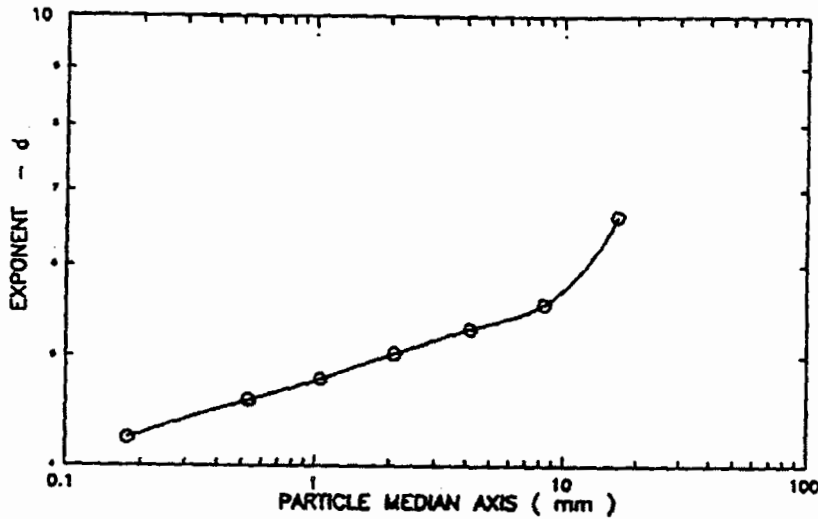


Fig. 4. Relationship Between Exponent d of Eqn. $B = C S^d$ and Size Fractions of the Bed Load Material for the Three Roaring River Data Sets

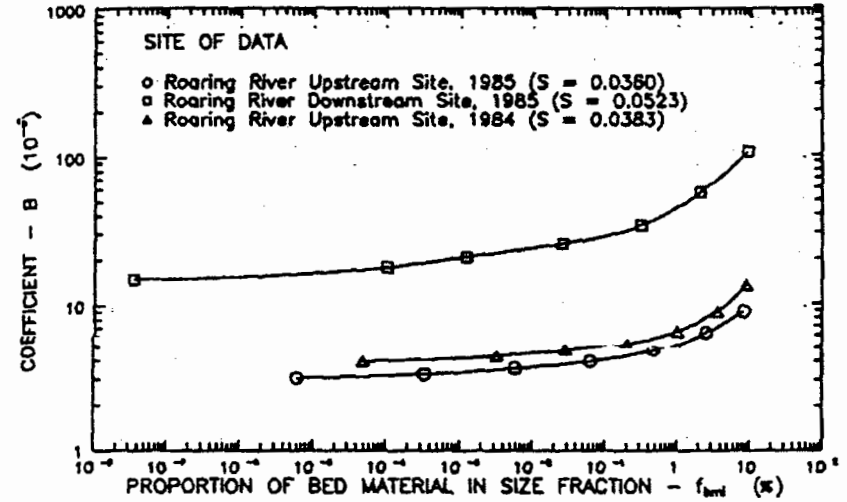


Fig. 5. Relationship Between Coefficient B of Eqn. $q_b = B(q - q_{ci})$ and Proportion of the Bed Material in Each Size Fraction for Three Roaring River Data Sets

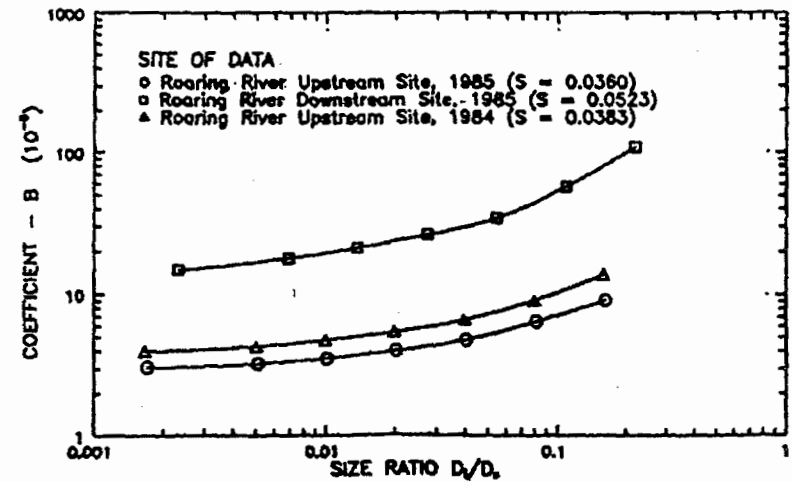


Fig. 6. Relationship Between Coefficient B of Eqn. $q_b = B(q - q_{ci})$ and the Bed Material Size Ratio D_i/D_r , for Three Roaring River Data Sets

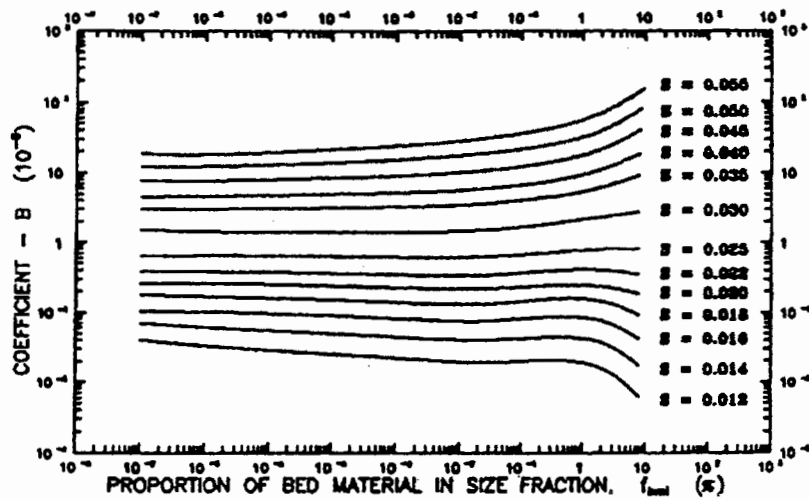


Fig. 7. Relationship Between Coefficient B of Eqn. $q_b = B(q - q_{ci})$, Slope S and Proportion of the Bed Material in Each Size Fraction f_{bmi} ;

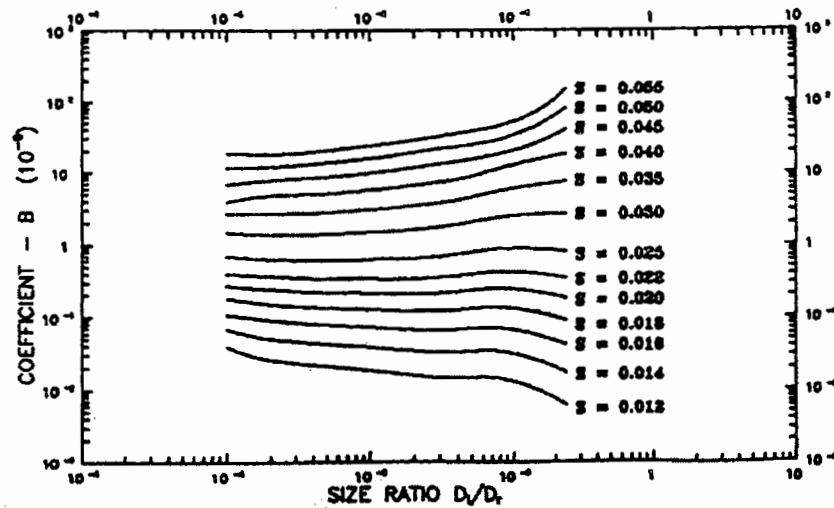


Fig. 8. Relationship Between Coefficient B of Eqn. $q_b = B(q - q_{ci})$, Slope S and Proportion of the Bed Material Size Ratio D_i/D_r .

With reference to the Schoklitsch (1962) equation (eqn. (6)), for the total bed load; Shih and Komar (1990) (eqn. (7)) and Wilcock and Southard (1989) (eqn. (8)) equations for bed load transport by size fraction, the bed load transport equation for size fraction that is proposed in eqn. (10) becomes

$$q_{bi} = f_{bli} B (q - q_{ci}) \dots \dots \dots (14)$$

where,

q_{bi} = unit bed load transport for size fraction i ($m^3/s/m$);

q = unit water discharge

q_{ci} = critical unit water discharge for size fraction i can be obtained by eqns. (1), (3) and (5)

f_{bli} = proportion of the bed load in size fraction i (%) and can be obtained by the standard normal distribution (Gauss distribution) and the Rosin distribution;

B = a coefficient = $f(f_{bmi}, S)$, can be obtained by Figs. 7 and 8;

f_{bmi} = proportion of the bed material in size fraction i (%) and can be obtained by the standard normal distribution (Gauss distribution) and the Rosin distribution;

S = slope.

TEST OF DERIVED RELATIONSHIP

Data collected in July, 1990 by the author, from the Pitzbach, Austria (Inpasihardjo, 1991), were used in an independent test and data from the Roaring River downstream site, 1985 are used in a semi-independent test of derived equation.

For the Pitzbach the reference diameter $D_r = D_{63}$ was used to obtain the critical unit water discharge for each size fraction, whereas for the Roaring River downstream site $D_r = D_{50}$ was used. The data of bed load discharge for both sites can be obtain from Inpasihardjo (1991).

Comparison of calculated values of unit bed load discharge by size fraction, which were obtained using eqn. (14) and Fig. 7 with the corresponding measured values is plotted in Figs. 9 - 17. The figures show the calculated values for the Roaring River downstream site are very close to a good agreement, while for the Pitzbach they indicate that the derived relationship can be used to calculate the bed load transport for each size fraction as well as the total bed load transport for gravel bed rivers.

DISCUSSION

This discussion on the developing a bed load transport equation applicable to each size fraction concerns three important parameters in natural rivers : bed material and bed load size distribution (distribution of size fractions in the mixture, f_{bmi} and f_{bli}) and channel slope S .

1. Effect of Bed Material and Bed Load Size Distributions

It is clear from the preceding section that bed load transport depend both bed material and bed load size distributions. It was found that the relative grain size effects are stronger than absolute size effects, therefore the proportion of each size fraction in the mixture has an important role in determining bed load transport in natural rivers.

The bed material size distribution can be assumed constant at a site. therefore the proportion of each size fraction can be obtained by the standard normal distribution (Gauss distribution) and the Rosin distribution (Shih and Komar, 1990)

2. Effect of Channel Slope

Channel slope is another parameter, which should be accounted for in the bed load transport equation. It is clear from Figs. 7 and 8 generally that for a constant proportion of the bed material in each size fraction, the value of coefficient B becomes bigger with increasing channel slope and becomes smaller with decreasing channel slope. In other words the bigger is the slope, the bigger is the bed load transport vice versa. Also it can be seen from Figs. 7 and 8 that for channel slope $S \leq 0,025$, the bigger is the proportion of the bed material in a given size fraction, or the bigger the size fraction itself (up to D_i) the bigger is the value of the coefficient B. The hiding/exposure effect therefore seems to be responsible for these conditions.

CONCLUSION

An equation for calculating the total unit bed load transport has been developed empirically in the form

$$q_b = B (q - q_{ci})$$

where q_b = total unit bed load transport; B is a function of (f_{bmi} , S) which can be obtained from Figs. 7 and 8; q = unit water discharge and q_{ci} = critical unit water discharge for size fraction i; calculated by eqns. (1), (3) and (5)

The bed load transport by size fraction can be obtained by distributing the total bed load transport into each size fraction using eqn. (14), written as

$$q_{bi} = f_{bii} q_b$$

where,

- q_{bi} = unit bed load transport for size fraction i;
- f_{bii} = proportion of bed load in size fraction i;
- q_b = total unit bed load transport;

It should be noted that the eqns. (11), (12), (13) and (14) were derived for the range of slope 0,036 – 0,0523 and range of bed load size distributions $22,4 \geq D_i$ (mm) $\geq 0,1875$. Preliminary analysis of the relationship in Fig. 5 (eqn. (12) was derived based

extensions to a wider range of slopes obtained by linear interpolation and extrapolation from available slopes. These are included as an investigation of the slope effect but should be used with caution.

However, the independent test with Pitzbach (slope $S = 0,0395$) data and semi-independent test with the data for the Roaring River downstream site, 1985 (slope $S = 0,046$) provide encouraging support for the relationship.

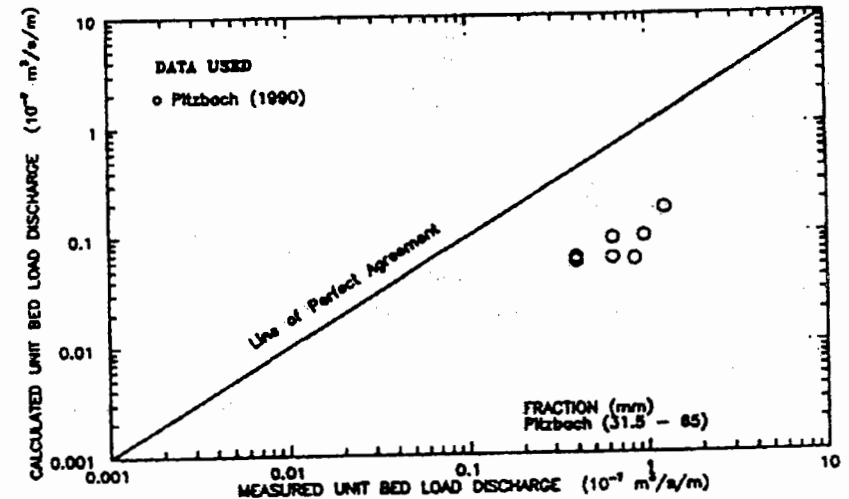


Fig. 9. Comparison of Measured Unit Bed Load Discharges with Unit Bed Load Discharges Calculated by Eqn. (14) for the Size Fraction Indicated

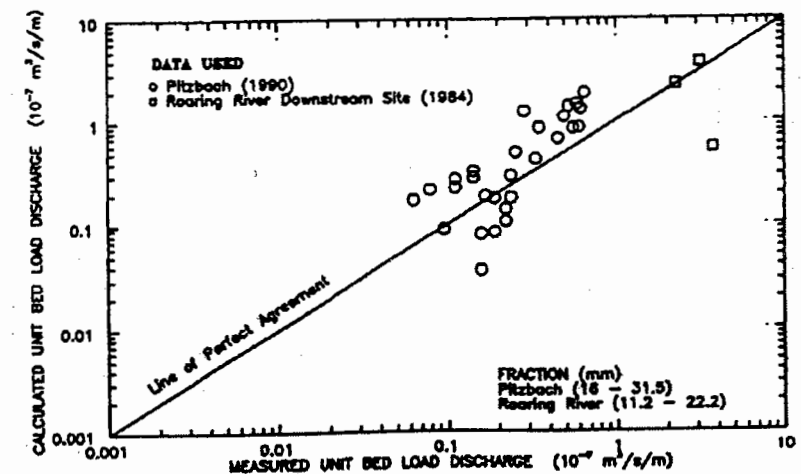


Fig. 10. Comparison of Measured Unit Bed Load Discharges with Unit Bed Load

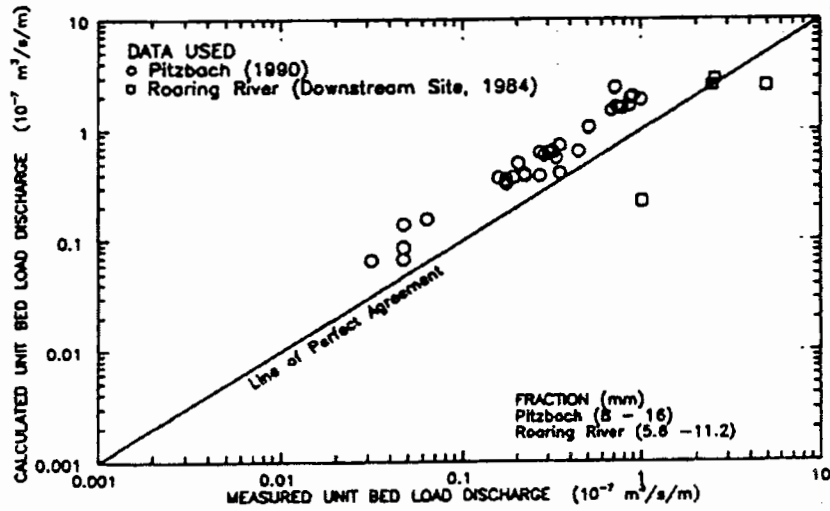


Fig. 11. Comparison of Measured Unit Bed Load Discharges with Unit Bed Load Discharges Calculated by Eqn. (14) for the Size Fraction Indicated

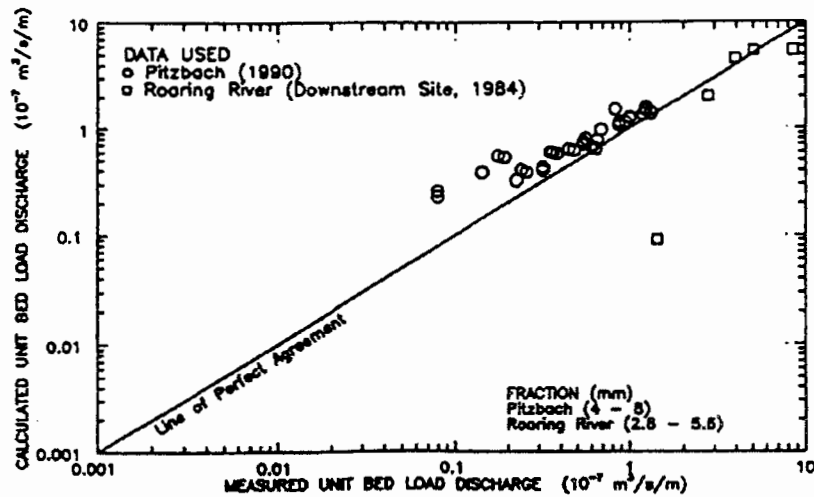


Fig. 12. Comparison of Measured Unit Bed Load Discharges with Unit Bed Load Discharges Calculated by Eqn. (14) for the Size Fraction Indicated

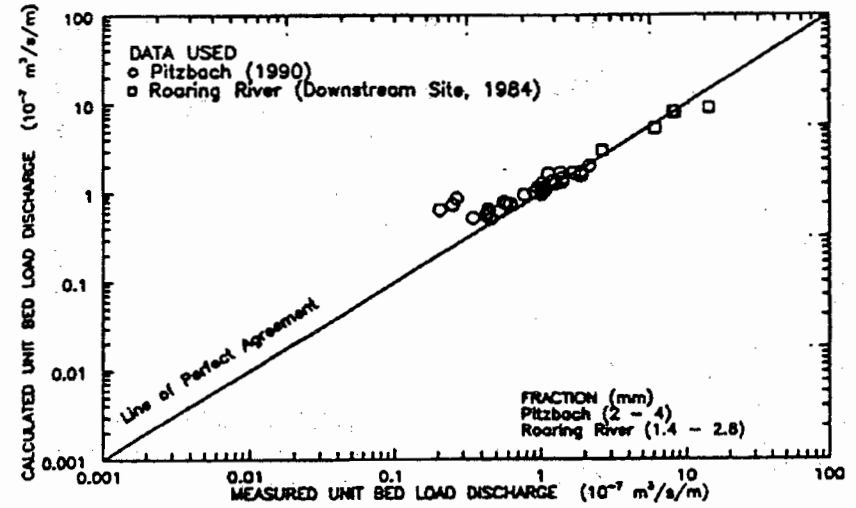


Fig. 13. Comparison of Measured Unit Bed Load Discharges with Unit Bed Load Discharges Calculated by Eqn. (14) for the Size Fraction Indicated

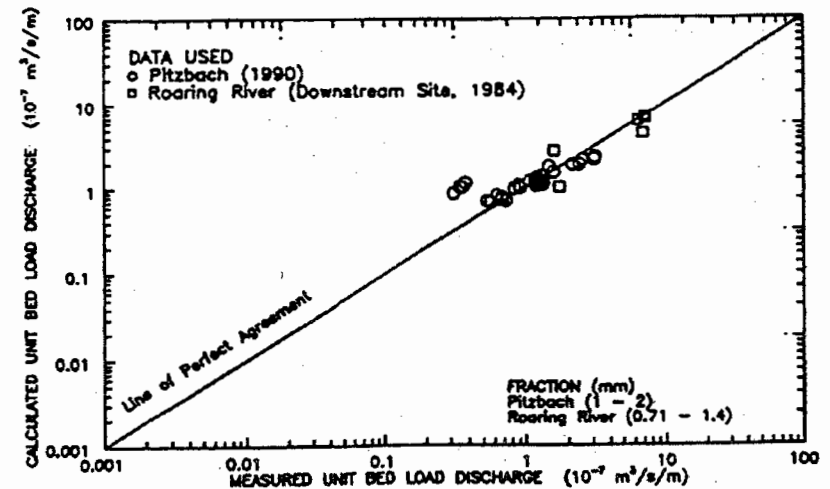


Fig. 14. Comparison of Measured Unit Bed Load Discharges with Unit Bed Load Discharges Calculated by Eqn. (14) for the Size Fraction Indicated

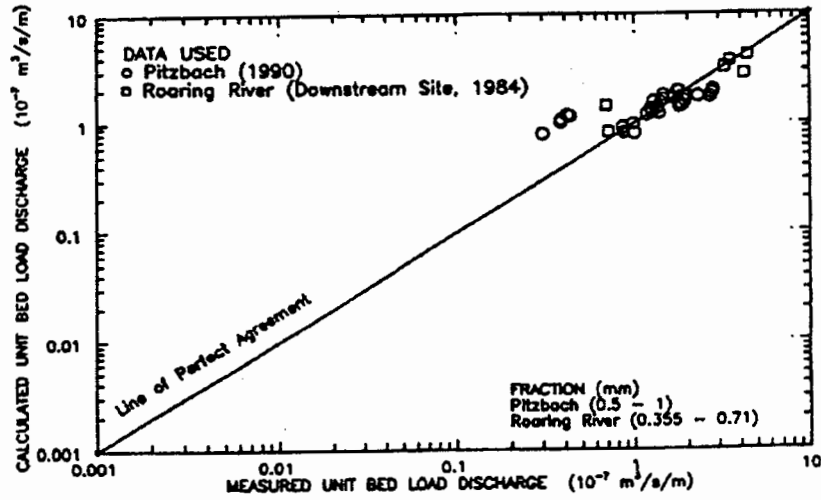


Fig. 15 Comparison of Measured Unit Bed Load Discharges with Unit Bed Load Discharges Calculated by Eqn. (14) for the Size Fraction Indicated

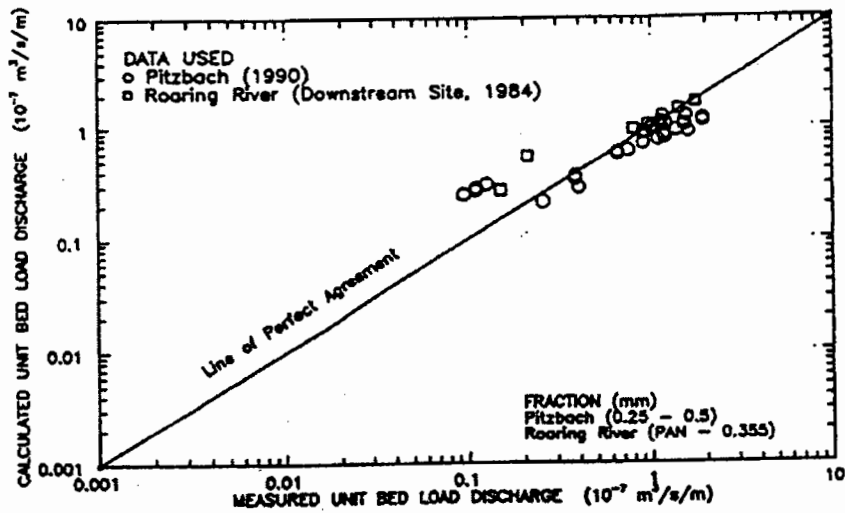


Fig. 16 Comparison of Measured Unit Bed Load Discharges with Unit Bed Load Discharges Calculated by Eqn. (14) for the Size Fraction Indicated

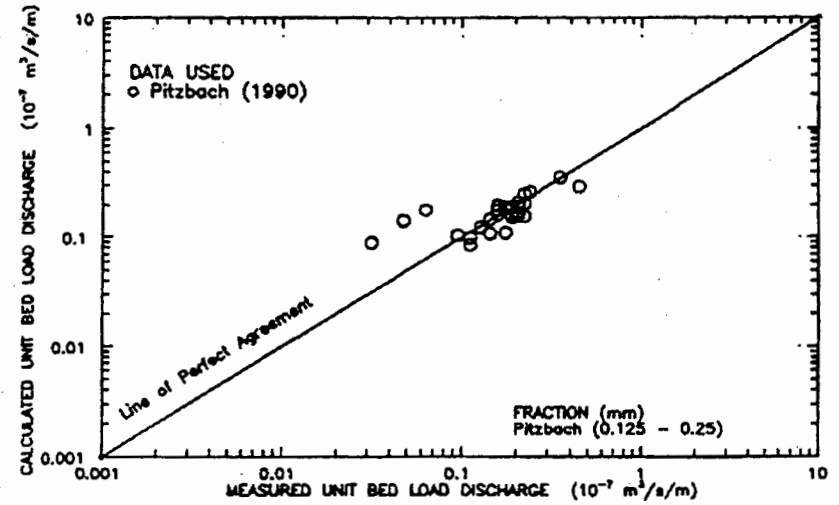


Fig. 17 Comparison of Measured Unit Bed Load Discharges with Unit Bed Load Discharges Calculated by Eqn. (14) for the Size Fraction Indicated

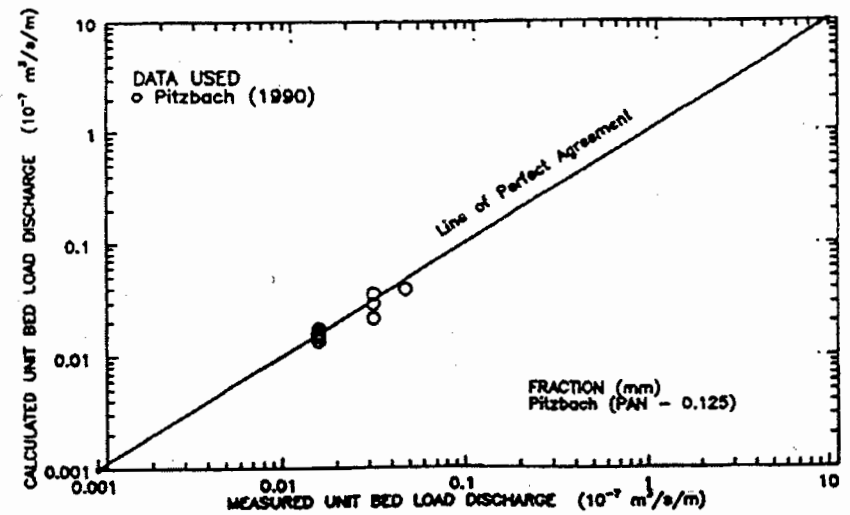


Fig. 18 Comparison of Measured Unit Bed Load Discharges with Unit Bed Load Discharges Calculated by Eqn. (14) for the Size Fraction Indicated

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