Bed-Material Load Computations for Nonuniform Sediments

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Abstract: The nonuniformity of bed material affects the bed-material load calculations. A size gradation correction factor K_d is developed to account for the lognormal distribution of bed material. The use of K_d in conjunction with bed-material load equations originally developed for single particle sizes improves the accuracy of transport calculations for sediment mixtures. This method is applicable to laboratory flumes and natural rivers with median diameter d_{50} of bed material in the sand size ranges. The improvement on transport rate by K_d factor is significant for data with standard deviation σ_g of bed material greater than 2, while the correction is negligible for data with σ_g less than 1.5. Sediment in transport also follows a lognormal distribution with a median diameter d_{50t} generally finer than the corresponding d_{50}. As the size gradation increases, d_{50t} becomes much finer than the corresponding value of d_{50}. The relationship between d_{50t} and d_{50} is defined as a function of σ_g and agrees well with field data. The previously recommended use of d_{35} as representative size of the bed material is found not to be generally applicable.

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Introduction

Riverbeds are usually composed of nonuniform sediment mixtures and the corresponding particle size distribution of sediment in transport is generally finer than the distribution of bed material because of selective transport. This makes the prediction of sediment load for natural rivers more difficult than for uniform sediment in laboratory flumes. To consider the effect of nonuniformity of bed material on sediment transport, various representative bed material sizes have been used for the computation of sediment transport rates. The commonly used representative sizes include: (1) the median diameter of bed material, d_{50}; (2) the diameter of bed material, d_{35}, for which 35% is finer as proposed by Einstein (1944) and Ackers and White (1973); (3) the mean diameter defined by Meyer-Peter and Müller (1948) as $d_m = \Sigma \Delta P_{bi} d_i$, where ΔP_{bi} is the fraction of bed material, by dry weight, corresponding to the size fraction i, and d_i is the representative diameter of bed material corresponding to the size fraction i; (4) the mean fall velocity defined by Han (1973) as $\omega_m = (\Sigma \Delta P_{bi} \omega_i^m)^{1/m}$, where ω_i is the fall velocity of particle of size d_i, and m is an exponent; and (5) the effective diameter defined by Nordin (1989) as $d_e = 1/(\Sigma \Delta P_{bi}/d_i)$.

The use of a single fixed size, such as d_{50} or d_{35}, may not be adequate in representing the various size fractions present in sediment mixtures. As pointed out by White and Day (1982), grading curves with different shapes will certainly have different effective diameters. The effective sediment size is also expected to vary with the transport rate or flow intensity. Therefore, in addition to d_{50}, a sediment nonuniformity factor expressed by d_{90}/d_{30} was used by Smart and Jaeggi (1983) to account for the effect of size distribution, and the size gradation coefficient defined by $G = 0.5(d_{84}/d + d_{50}/d_{16})$ was used by Shen and Rao (1991), where d_p is diameter for which p percent of bed material is finer. The factors d_{90}/d_{30}, G, and others describing the gradation of mixtures are all believed to be significant in the transport of sediment mixtures because they represent to some extent the shape and range of particle sizes which are significantly present in the bed material.

Instead of using a single fixed size or a single fixed size with a size gradation parameter as the representative property of bed material, van Rijn (1984), Hsu and Holly (1992), Molinas and Wu (1998), and Wu (1999) suggested the use of variable representative sizes for the computation of sediment transport rates for sediment mixtures. The variable representative size is analogous to the median size or other characteristic sizes of sediments in transport. It is believed that the variable representative size is a better representation of the sediment mixture than not only a fixed particle diameter such as d_{35} or d_{50} of bed material, but also the simple combination of a fixed representative size and a size gradation factor.

In the development of a suspended load transport equation, van Rijn (1984) proposed an empirical equation to estimate the representative diameter d_s for suspended sediment load. The equation was determined by trial and error to give the same value for the suspended load as that computed with Einstein's method. This equation is expressed as

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$$\frac{d_s}{d_{50}} = 1 + 0.011(G-1)(T-25) \tag{1}$$

where T = transport stage parameter defined by $T=(\tau'-\tau_c)/\tau_c$; and τ' and τ_c = grain shear stress and critical shear stress, respectively.

Hsu and Holly (1992) performed an interesting study on the bedload transport for sediment mixtures. In their study, they proposed a model for the computation of the mean size, d_{mt}, of sediments in transport. Based on observation of sediment-mixture experiments, Hsu and Holly (1992) postulated that the fraction of each size class in transported material is proportional to the joint probability of the relative mobility (ΔP_{moi}) of each particle size and the availability (ΔP_{bi}) of each size class on the bed surface. From this concept, they expressed the size distribution of the transported bedload sediments as

$$\Delta P_{ci} = \frac{\Delta P_{moi}\Delta P_{bi}}{\sum_{i=1}^{N}(\Delta P_{moi}\Delta P_{bi})} \tag{2}$$

where

$$\Delta P_{moi} = \frac{1}{\sigma\sqrt{2\pi}}\int_{(V_{ci}/V)-1}^{\infty}\exp\left(-\frac{x^2}{2\sigma}\right)dx = 0.5 - 0.5\ \mathrm{erf}\left(\frac{\frac{V_{ci}}{V}-1}{\sigma\sqrt{2}}\right) \tag{3}$$

where erf(z) = error function; V = cross-sectional average velocity; V_{ci} = incipient velocity for a particular size class i in a mixture; σ = standard deviation of V'/V distribution; and V' = absolute fluctuations of velocity.

From the size distribution computed utilizing Eq. (2), the mean size d_{mt} can be determined. Hsu and Holly argued that if d_{mt} is visualized as the representative property of a uniform sediment, the bedload discharge could be evaluated using any appropriate bedload equations.

Molinas and Wu (1998) developed a size gradation compensation factor to incorporate the effect that the size distribution has on the transport of sediment mixtures. The resulting equivalent representative diameter, d_e, can be expressed as

$$d_e = \frac{1.8d_{50}}{1 + 0.8(V_*/\omega_{50})^{0.1}(\sigma_g-1)^{2.2}} \tag{4}$$

where V_* = shear velocity; σ_g = dimensionless standard deviation of bed material, which is equal to $\sqrt{d_{84}/d_{16}}$; and ω_{50} = fall velocity of sediment corresponding to particle size d_{50}. This equivalent representative diameter was proposed for existing sediment transport formulas to produce more accurate prediction of transport rats for nonuniform mixtures.

In the proceeding approaches, the ultimate goal in defining a variable representative size is to improve the prediction of sediment transport rates for nonuniform mixtures. Unfortunately, the representative size of Eq. (1) is developed based on the results computed with Einstein's method; and it is limited to suspended load. The representative size based on Eq. (2) proposed by Hsu and Holly is for bed load; and although representing a promising approach it is not verified with measurements. The equivalent diameter given by Eq. (4) was mainly developed to compensate for sediment nonuniformity effects for existing transport formulas in bed-material load computations, so it lacks generality.

In this paper, the effect of bed material nonuniformity on the transport of sediment mixtures in sand-bed channels is studied. A size gradation correction factor is derived based on the lognormal distribution of bed material. The median diameter d_{50t} of sediment in transport and the variable representative size for the computation of bed-material load are discussed.

Lognormal Size Distribution of Bed Material

The particle size distribution of bed material is generally skewed (Mahmood 1973a,b). Particle size distributions can often be converted into symmetrical, nearly Gaussian (normal) distribution by a logarithmic transformation. The corresponding particle size distribution in this case is called a lognormal particle size distribution.

Two examples of the lognormal particle size distribution are presented in Fig. 1. The data shown in Fig. 1 were obtained in Rio Grande near Bernalillo, New Mexico on June 1, 1953 and June 18, 1958, respectively (Nordin and Beverage 1965). The frequency distributions displayed in Figs. 1(a and c) are obviously skewed. However, when the particle diameters are plotted on a logarithmic scale against the frequency of occurrence, bell-shaped curves or lognormal curves as shown in Figs. 1(b and d) are generated. Fig. 2 shows the normalized log-probability plot of a large number of bed materials from Rio Grande. It can be seen that the size distribution from 10th to 90th percentile is closely approximated by lognormal distribution. This type of lognormal bed material size distributions is often encountered in most alluvial rivers with sand sediments.

If two variables x and y are related such that $y=\ln(x)$, where $0<x<\infty$, and if y follows a Gaussian distribution with mean μ_y and standard deviation σ_y given by

$$F_y(y) = \int_{-\infty}^{y}\frac{1}{\sigma_y\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{u-\mu_y}{\sigma_y}\right)^2\right]du \tag{5}$$

then, variable x is lognormally distributed as

$$F_x(x) = \int_{0}^{x}\frac{1}{\sigma_y v\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{\ln(v)-\mu_y}{\sigma_y}\right)^2\right]dv \tag{6}$$

where u and v = dummy variables of integration.

The bed material size distributions shown in Figs. 1 and 2 can be best described by the cumulative distribution function (CDF) of lognormal distribution expressed by Eq. (5) or (6) given that x is the particle size. The lognormal distribution is a skewed distribution and the two parameters required to define this distribution are μ_y and σ_y. In defining sediment mixtures, the median diameter d_{50} and the geometric standard deviation σ_g of the bed material are commonly reported. For this two-parameter lognormal distribution, it can be shown that d_{50} and σ_g are related to μ_y and σ_y as

$$\mu_y = \ln(d_{50}) \tag{7}$$

and

$$\sigma_y = \ln(\sigma_g) \tag{8}$$

In other words for naturally occurring sediment mixtures, the lognormal distribution is defined by d_{50} and σ_g.

By a simple transformation, the distribution expressed by Eq. (5) can be written as a standard normal distribution $N(0,1)$. Thus when $z=(y-\mu_y)/\sigma_y$, $dy=\sigma_y dz$, the probability density function becomes

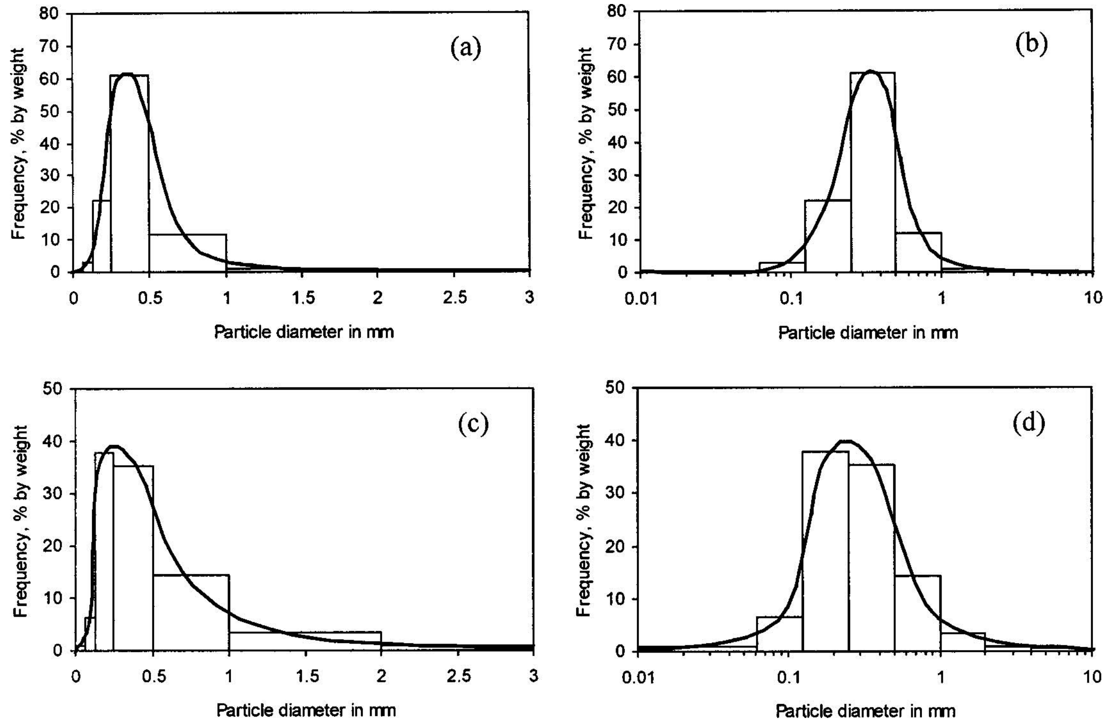

Fig. 1. Frequency histogram of bed-material size distribution for samples obtained in Rio Grande near Bernalillo, New Mexico: (a) and (b) Data observed on June 1, 1953, $d_{50}=0.33$ mm, $\sigma_g=1.62$; (c) and (d) data observed on June 18, 1958, $d_{50}=0.25$ mm, $\sigma_g=1.4$

$$f(z) = \frac{1}{\sqrt{2\pi}} e^{-z^2/2} \tag{9}$$

and the CDF

$$F_z(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-u^2/2} du \tag{10}$$

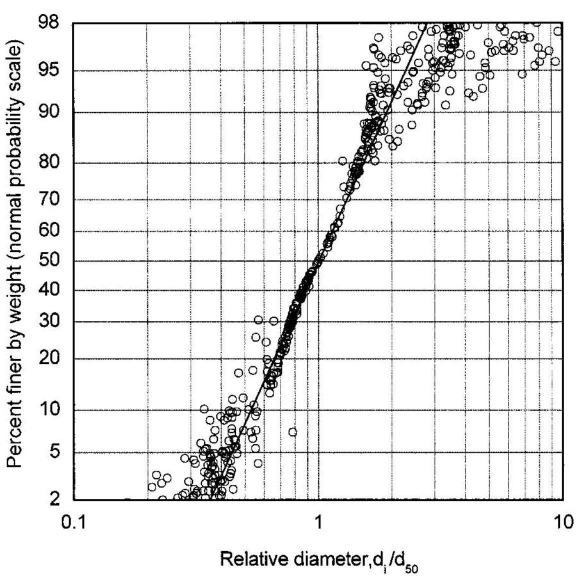

Fig. 2. Bed-material size distribution plotted on log-probability paper for the 112 samples measured over 1952–1962 in Rio Grande at Albuqerque and Bernalillo, New Mexico ($d_{50}=0.18-0.43$ mm, $\sigma_g=1.36-2.78$, actual sizes normalized to yield $\sigma_g=1.8$)

The variable z is called the standard unit, which is normally distributed with zero mean and unit standard deviation.

Effects of Nonuniformity of Bed Material

There are two types of methods commonly used to compute the transport rates for nonuniform mixtures. The first type of method is based on the computation of transport rates for each size fraction present in the nonuniform mixture. After knowing the transport rates corresponding to each size fraction, the total bed-material transport rate is determined by summation of the fractional transport rates. The classical Einstein method (Einstein 1950) is an excellent example in this category. This type of method was generally found unsatisfactory in predictions of total bed-material transport rate for sediment mixtures due to the complexity of transport of sediment mixtures and the lack of knowledge concerning the motion of individual size and its effect on other sizes (Misri et al. 1984; Samaga et al. 1986b; Swamee and Ojha 1991).

The second type of methods computes the total bed-material transport rate based on a single representative size for graded sediment mixtures. They usually can produce more reliable predictions and have been widely used in practice. The formula of Engelund and Hansen (1967) developed based on the median bed material size d_{50} is well known in this category. It can be expressed as

$$f' \ \Phi = 0.1\theta^{2.5} \tag{11}$$

where

$$\theta = \frac{\tau}{(\gamma_s - \gamma)d_{50}} \tag{12}$$

$$\Phi = \frac{q_t}{\gamma_s \sqrt{(s_g - 1) g d_{50}^3}} \tag{13}$$

where f' = friction factor defined by Engelund and Hansen; θ = dimensionless shear parameter; Φ = dimensionless sediment transport function; τ = shear stress along the bed; g = gravitational acceleration; q_t = total bed-material sediment discharge by weight per unit width; s_g = specific gravity given by γ_s/γ; and γ and γ_s = specific weight of water and sediment, respectively.

Conceptually the Engelund and Hansen method can be applied to compute the fractional transport rates for nonuniform sediment mixtures by replacing d_{50} with the average (or geometric mean) diameter d_i of the corresponding size fraction. This concept assumes that a channel bed can be considered as a hypothetical mixture of sediment particles; the mixture can be formed into class intervals by size, and a potential transport capacity can be calculated for each class interval, whether or not particles are physically present. Subsequently, particle availability can be evaluated and expressed as ΔP_{bi}. Availability and potential transport capacity can then be combined to give transport capacity as follows:

$$Q_s = \sum_{i=1}^{N} Q_{si} = \sum_{i=1}^{N} \Delta P_{bi} Q_{spi} \quad \text{or} \quad Q_s = \int_{-\infty}^{\infty} Q_{sp} f(u) du \tag{14}$$

where Q_s = total bed-material transport rate; Q_{si} = fractional bed-material transport rate; Q_{spi} = potential bed-material transport rate for size fraction i assuming uniform sediment of size d_i under identical hydraulic conditions; i denotes the size fraction number in a mixture; N = number of size fractions present in the sediment mixture; and $f(u)$ = density function of lognormal size distribution expressed by Eq. (9). The concept expressed by Eq. (14) neglects the sheltering-exposure effects in rivers with mixed sizes. Fortunately, this phenomenon is not significant in sand-bed rivers since the nonuniform sediment is commonly under full motion. Keep this in mind, further justifications are needed if this concept is to be extended to gravel-bed rivers.

According to the Engelund and Hansen equation, the sediment transport rate is inversely proportional to particle diameter d, i.e. $Q_s \propto d^{-1}$. If another form of the Englund and Hansen equation $f'\Phi = 0.3\theta^2\sqrt{\theta^2 + 0.15}$ is considered, then we get $f'\Phi \sim \theta^2$ for small θ and $f'\Phi \sim \theta^3$ for large θ (Chien and Wan 1999), resulting in $Q_s \propto d^{-(0.5-1.5)}$. In addition, the methods by Bagnold (1966), Velikanov (1954), and Dou (1974) show that Q_s is inversely proportional to ω, while Zhang (1959) and Zhang and Xie (1993) indicates $Q_s \propto \omega^{-(0.5-1.5)}$ and Molinas and Wu (2001) gives $Q_s \propto \omega^{-(1-1.5)}$, where ω is the fall velocity of sediment. Considering $\omega \propto d^{0.5-2}$ ($\omega \propto d^2$ for $d < 0.1$ mm and $\omega \propto d^{0.5}$ for $d > 1.0$ mm), it is more general to assume that

$$Q_s \propto C d^{-b} \tag{15}$$

where C = integrated coefficient; and b = exponent.

It is expected that differences exist between the total bed-material transport rate Q_s obtained from Eq. (14) and from equation like Eq. (11) based on d_{50}. Lets denote K_d the ratio of Q_s obtained by these two different methods, i.e.

$$K_d = \frac{Q_s \text{ by size frations for lognormal distribution}}{Q_s \text{ based on } d_{50}} = \frac{\int_{-\infty}^{\infty} Q_{sp} f(u) du}{Q_{s50}} \tag{16}$$

Considering that $Q_{sp} \propto C d^{-b}$ and $Q_{s50} \propto C d_{50}^{-b}$, Eq. (16) can be expressed as

$$K_d = \int_{-\infty}^{\infty} \left(\frac{d}{d_{50}}\right)^{-b} f(u) du \tag{17}$$

From the definition of z we have

$$z = \frac{y - \mu_y}{\sigma_y} = \frac{\ln d - \ln d_{50}}{\ln \sigma_g} \quad \text{or} \quad \frac{d}{d_{50}} = \sigma_g^z \tag{18}$$

Thus

$$\begin{aligned} K_d &= \int_{-\infty}^{\infty} \sigma_g^{-ub} f(u) du \\ &= \int_{-\infty}^{\infty} \sigma_g^{-ub} \frac{1}{\sqrt{2\pi}} e^{-0.5u^2} du \\ &= \int_{-\infty}^{\infty} e^{-bu \ln \sigma_g} \frac{1}{\sqrt{2\pi}} e^{-0.5u^2} du \\ &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-0.5u^2 - bu \ln \sigma_g} du \\ &= e^{0.5(b \ln \sigma_g)^2} \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-0.5(u + b \ln \sigma_g)^2} du \end{aligned} \tag{19}$$

Finally, we get

$$K_d = e^{0.5(b \ln \sigma_g)^2} \tag{20}$$

The earlier equation shows that K_d increase with the increase in σ_g values, having a minimum value of 1 corresponding to uniform distribution or $\sigma_g = 1$. This means that a sediment transport equation developed for uniform sediments based d_{50} usually underpredicts the transport rate for nonuniform mixtures. As such, K_d can be used as a correction factor to obtain the correct prediction for nonuniform sediment mixtures in conjunction with a sediment transport equation, such as the Engelund and Hansen equation, originally developed for uniform sediment.

Characteristc Particle Sizes

The size distribution of sediment in transport is different from that of bed material. Consequently, the median diameter of sediment in transport is different from that of the bed material. Similar to Eq. (16), the CDF of sediment in transport can be obtained by

$$F_t(z) = \frac{\int_{-\infty}^{z} Q_{sp} f(u) du}{\int_{-\infty}^{\infty} Q_{sp} f(u) du}$$

$$= \frac{(Cd_{50}^{-b}) e^{0.5(b \ln \sigma_g)^2} \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-0.5u^2 - bu \ln \sigma_g} du}{(Cd_{50}^{-b}) e^{0.5(b \ln \sigma_g)^2} \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-0.5u^2 - bu \ln \sigma_g} du} \tag{21}$$

or

$$F_t(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-0.5(u + b \ln \sigma_g)^2} du \tag{22}$$

Eq. (22) indicates that the sediment in transport also has a lognormal distribution. The 50 percentile of the particle size distribution of transported sediment d_{50t} corresponds to the value of z in Eq. (22) that gives $F_t(z) = 0.5$, i.e.

$$0.5 = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-0.5(u + b \ln \sigma_g)^2} du \tag{23}$$

Denoting $\zeta = z + b \ln \sigma_g$, then $dz = d\zeta$, Eq. (23) becomes

$$0.5 = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\zeta} e^{-0.5v^2} dv \tag{24}$$

Eq. (24) is a standard normal distribution. It can hold only when $\zeta = 0$ or $z + b \ln \sigma_g = 0$. Thus substituting $z = -b \ln \sigma_g$ into Eq. (18) results in

$$\frac{d_{50t}}{d_{50}} = \sigma_g^{-b \ln \sigma_g} \tag{25}$$

Eq. (25) describes the relationship between d_{50t} and d_{50}. There exists a bed material size which matches d_{50t}. In order to determine the bed material size corresponding to d_{50t}, a bed material size is set equal to d_{50t} and the corresponding percentage is computed.

According to Eq. (18), the pth percentile of the sediment size distribution d_p can be determined by

$$d_p = d_{50} \sigma_g^{\xi_p} \tag{26}$$

where $\xi_p = p$th percentile of standard normal distribution $[\sim N(0,1)]$.

For $P < 50\%$, the value of ξ_p in Eq. (26) is negative which results in a value of d_p smaller than the corresponding value of d_{50}. For $P > 50\%$, the value of ξ_p is positive which gives d_p greater than d_{50}. Assuming $d_p = d_{50t}$ and combining Eqs. (25) and (26) yields

$$\sigma_g^{\xi_p} = \sigma_g^{-b \ln(\sigma_g)} \tag{27}$$

and

$$\xi_p = -b \ln(\sigma_g) \tag{28}$$

Using the value of ξ_p given by Eq. (28) as the upper boundary for the standard normal distribution, the percentage for which the diameter of bed material corresponds to d_{50t} for a given σ_g can be determined by

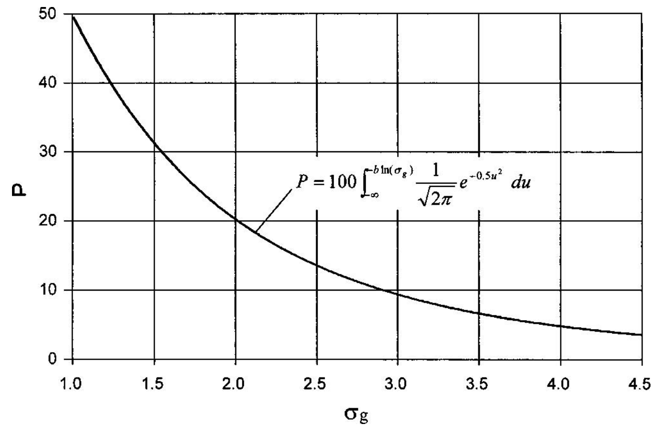

Fig. 3. Percentage of the diameter of bed-material that equals to median diameter of sediment in transport $(b = 1.2)$

$$P = 100 \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\xi_p} e^{-0.5u^2} du \tag{29}$$

Substituting Eq. (28) into Eq. (29) yields

$$P = 100 \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{-b \ln(\sigma_g)} e^{-0.5u^2} du \tag{30}$$

The relationship between P and σ_g given by Eq. (30) is shown in Fig. 3. For uniform sediment, $P = 50\%$ which means that the median size, d_{50t}, of sediment in transport is equal to the median diameter d_{50} of bed material. As the value of σ_g increases the P value decreases, resulting in a smaller bed material diameter that equals to d_{50t}.

An appropriate variable representative diameter d_e may be used for the computation of sediment transport rates for sediment mixtures. The use of d_e is equivalent to the K_d factor to account for the effect of size gradation, resulting in $K_d Q_{s50} = Q_{sd_e}$. Considering that $Q_{s50} \propto C d_{50}^{-b}$ and $Q_{sd_e} \propto C d_e^{-b}$, the variable representative diameter now can be expressed as

$$\frac{d_e}{d_{50}} = e^{-0.5b(\ln \sigma_g)^2} \tag{31}$$

It is mentioned earlier that Einstein (1944) and Ackers and White (1973) suggested the use of d_{35} as the representative size in sediment load computations for nonuniform mixtures. For this special case, $P = 35\%$ and $\xi_p = -0.385$, which results in, according to Eq. (26), the following relation

$$\frac{d_{35}}{d_{50}} = \sigma_g^{-0.385} \tag{32}$$

Test of the Correction Factor

The exponent b may be determined based on measured data for fractional transport rates for sediment mixtures since this paper focuses on effects of sediment nonuniformity. For this purpose the relative fractional transport rates/capacities of each data set in selected laboratory experiments and natural rivers are plotted in Fig. 4 to check the variation of transport capacities with sediment sizes. The procedure to find the relative transport capacity for each size is illustrated in Table 1. In this table the values of d_i, ΔP_{bi}, Q_{si} are direct measurements, Q_{spi} is computed by $Q_{si}/\Delta P_{bi}$.

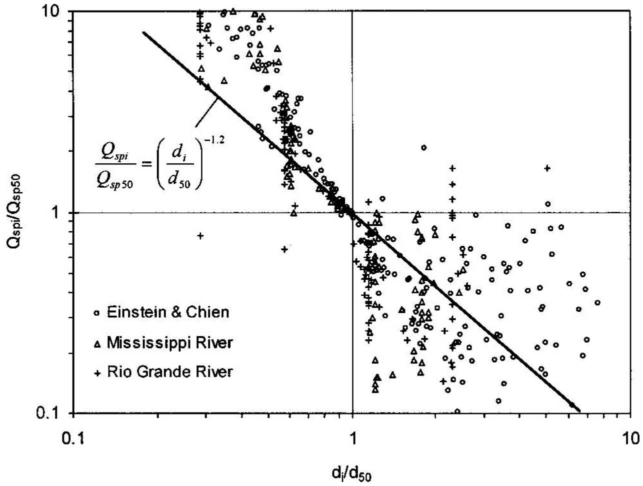

Fig. 4. Variation of fractional transport capacity with relative particle size

It can be seen from Fig. 4 that majority of the data sets show a similar trend in which the relative transport capacity decreases with the increase of particle size. A trend line may be drawn for the data shown in the figure, i.e.

$$\log\frac{Q_{spi}}{Q_{sp50}} = -1.2\log\frac{d_i}{d_{50}} \quad \text{or} \quad \frac{Q_{spi}}{Q_{sp50}} = \left(\frac{d_i}{d_{50}}\right)^{-1.2} \tag{33}$$

This results in a value of b in Eq. (20) to be 1.2. It is expected that b should vary with particle size and flow intensity, showing nonlinear variation. However, for simplicity it is assumed to be a constant value in this paper. Since the Engelund and Hansen equation was developed based on relatively uniform sediments in the sand range, the validity of K_d correction should be tested using nonuniform sediments in sand range and with relatively high σ_g values. It is expected that the sediment transport rate would be underestimated by Engelund and Hansen's original equation. The use of K_d would then produce better predictions by accounting for the effects of nonuniformity of bed material.

Even though a lot of laboratory and field sediment transport data for sand sizes can be found in the literature, only a few have relatively high σ_g values. After careful review, the laboratory data

Table 1. An Example to Illustrate the Computation of Relative Transport Rates for Measured Data

Representative diameter of group I d_i (mm)	Relative diameter d_i/d_{50}	Size fraction of group i ΔP_{bi}	Fractional transport rate Q_{si} (kg/s/m)	Potential transport capacity Q_{spi} (kg/s/m)	Relative transport capacity Q_{spi}/Q_{sp50}
0.037	0.181	0.044	1.679	38.250	37.150
0.052	0.259	0.050	1.083	21.530	20.910
0.067	0.332	0.041	0.542	13.310	12.930
0.088	0.433	0.094	0.650	6.898	6.700
0.124	0.610	0.129	0.347	2.698	2.620
0.175	0.863	0.154	0.206	1.335	1.297
0.248	1.223	0.167	0.089	0.532	0.517
0.351	1.732	0.123	0.043	0.352	0.342
0.496	2.447	0.102	0.026	0.256	0.248
0.701	3.458	0.062	0.020	0.314	0.305
0.986	4.870	0.034	0.012	0.348	0.338

Note: The data is extracted from Einstein and Chien's Laboratory Data No. 22, d_{50}=0.135 mm; $Q_{spi}=Q_{si}/\Delta P_{bi}$; and Q_{sp50}=potential transport capacity corresponding to d_{50}.

Table 2. Summary of Laboratory and Field Data Used for Testing K_d Correction

Data source	Flow discharge (m^3/s)	Flow depth (m)	Median diameter of bed material (mm)	Geometric standard deviation of bed material	Bed-material concentration	Number of data sets
		(a) Laboratory data				
Einstein and Chien (1953)	0.043–0.066	0.18–0.21	0.10–0.37	1.41–2.95	2,115–57,970	22
Samaga et al. (1986a,b)	0.0056–0.015	0.056–0.10	0.21–0.40	1.58–2.46	3,392–10,260	33
		(b) River data				
Atchafalaya River (Toffaleti 1968)	382–14,190	6.10–14.75	0.091–0.31	1.50–1.93	0.6–567	72
Mississippi River at Tarbert Landing (Toffaleti 1968)	4,248–28,830	6.74–16.40	0.178–0.327	1.38–2.00	12–262	53
Rio Grande River (Toffaleti 1968)	35.1–286.0	0.33–1.46	0.214–0.387	1.62–1.88	463–4,530	38
American Canal (Simon 1957)	1.22–29.4	0.80–2.59	0.096–0.715	2.01–3.85	44–448	12
Total of laboratory and river	0.0056–28,830	0.056–16.4	0.091–0.715	1.38–3.85	0.6–57,970	230

Table 3. Summary of Comparison between Computed and Measured Bed-Material Concentrations for Laboratory Data

Method	Data source	Data in range of discrepancy ratio R_i (%) 0.75–1.25	0.5–1.5	0.25–1.75	0.5–2.0	Average geometric deviation	Root mean square	Number of data sets
Engelund and Hansen equation based on D_{50}	Einstein & Chien	13.6	50.0	81.8	50.0	2.34	16,580	22
	Smaga et al.	27.3	90.9	100.0	90.9	1.52	2,403	33
	All laboratory data	21.8	74.6	92.7	74.6	1.80	10,650	55
Engelund and Hansen equation corrected by K_d	Einstein & Chien	45.5	68.2	86.4	72.7	1.66	12,810	22
	Samaga et al.	84.9	100.0	100.0	100.0	1.14	1,108	33
	All laboratory data	69.1	87.3	94.6	89.1	1.33	8,149	55

by Einstein and Chien (1953) and (Samaga et al. 1986a,b) and the river data from Atchafalaya River (Toffaleti 1968), Mississippi River at Tarbert Landing (Toffaleti 1968), Rio Grande River (Toffaleti 1968), American Canal (Simons 1957) were selected, see Table 2. The σ_g values of laboratory data by Einstein and Chien and Samaga et al. are in the range of 1.4–3.0 and 1.6–2.5, respectively, with most data points bigger than 2.0; the d_{50} values are in the range of 0.10–0.37 and 0.21–0.40 mm, respectively. The σ_g values of river data from Atchafalaya River, Mississippi River, Rio Grande River, American Canal are in the range of 1.5–1.9, 1.4–2.0, 1.6–1.9, and 2.0–3.9, respectively; the d_{50} values are in the range of 0.178–0.327, 0.214–0.387, and 0.096–0.715 mm, respectively.

The values of K_d calculated from Eq. (20) are 1.08, 1.41, 1.83, and 2.38 for σ_g value of 1.5, 2, 2.5 and 3, respectively. From this result, it is easy to conclude that the correction on transport rate by K_d factor is negligible for data with σ_g value less than 1.5, while the improvement is significant for data with σ_g value greater than 2.0.

The comparisons of results obtained by using the K_d factor with the measurements are given in Table 3 for laboratory and Table 4 for field data. In these tables, three statistical parameters are used to indicate the goodness-of-fit between the computed and measured results. These three statistical parameters are:

1. The discrepancy ratio

$$R_j = C_{tcj}/C_{tmj} \tag{34}$$

where C_{tc} and C_{tm} are the computed and measured bed-material concentrations, respectively; and j is the data set number.

2. The geometric standard deviation

$$AGD = \left(\prod_{j=1}^{J} RR_j\right)^{1/J}, \quad RR_j = \begin{cases} C_{tcj}/C_{tmj} & \text{for } C_{tcj} \geqslant C_{tmj} \\ C_{tmj}/C_{tcj} & \text{for } C_{tcj} < C_{tmj} \end{cases} \tag{35}$$

where J is the total number of data sets.

3. The root mean square

$$\text{RMS} = \left[\sum_{j=1}^{J} (C_{tcj} - C_{tmj})^2 \Big/ J\right]^{1/2} \tag{36}$$

From Table 3 it can be seen that the average geometric deviation and the root mean square between computed and measured bed-material concentrations were reduced from 2.34 and 16,580 to 1.66 and 12,810, respectively, for the Einstein and Chien data, and from 1.52 and 2,403 to 1.14 and 1,108, respectively, for the Samaga et al. data. The improvement in discrepancy ratio happened in all ranges. Taking the range of 0.5–2.0 as an example, the improvement was from 50.5 to 72.7% for the Einstein and Chien data, and from 90.9 to 100.0% for the Samaga et al. data.

Similar improvement was observed in river data as indicated in Table 4. The average geometric deviation and the root mean square were reduced from 2.03 and 568 to 1.78 and 492, respectively, for all river data. The improvement in discrepancy ratio in the range of 0.5–2.0 was from 56.0 to 67.4% for all river data.

Figs. 5 and 6 are the graphical comparisons of the results. Significant improvements for laboratory data by using K_d correction were demonstrated in Fig. 5. Improvements in predictions for river data can also be observed in Fig. 6. The improvement for the data from the American Canal was higher than for data from other rivers. The relatively small improvements by K_d factor for the Atchafalaya River and Mississippi River were partially resulted

Table 4. Summary of Comparison between Computed and Measured Bed-Material Concentrations for River Data

Method	Data source	Data in range of discrepancy ratio R_i (%) 0.75–1.25	0.5–1.5	0.25–1.75	0.5–2.0	Average geometric deviation	Root mean square (ppm)	Number of data sets
Engelund and Hansen equation based on D_{50}	Atchafalaya River	9.7	36.1	79.2	40.3	2.46	112	72
	Mississippi River	17.0	64.2	94.3	66.0	1.83	68	53
	Rio Grande River	44.7	73.9	100.0	76.3	1.53	120	38
	American Canal	16.7	41.7	66.7	41.7	2.50	172	12
	All river data	20.0	53.1	87.4	56.0	2.03	568	175
Engelund and Hansen equation corrected by K_d	Atchafalaya River	18.1	48.6	83.3	51.4	2.17	102	72
	Mississippi River	43.4	77.4	94.3	79.2	1.57	59	53
	Rio Grande River	31.6	79.0	97.4	86.8	1.44	104	38
	American Canal	16.7	50.0	75.0	50.0	1.89	150	12
	All river data	28.6	64.0	89.1	67.4	1.78	492	175

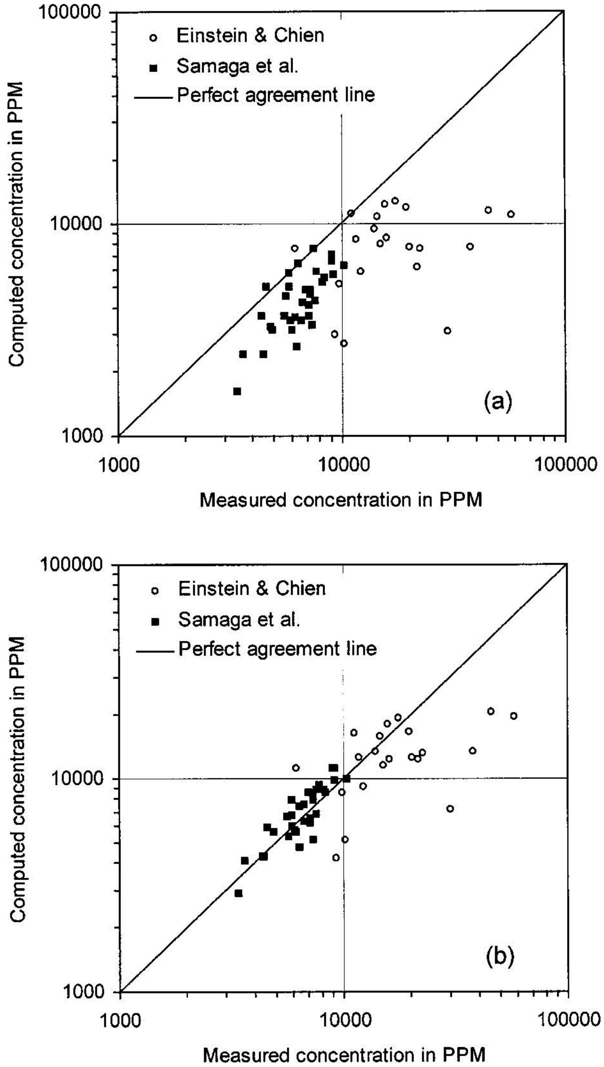

Fig. 5. Comparison between computed and measured bed-material concentration for the Engelund and Hansen Equation applied to laboratory data: (a) based on d_{50} and (b) corrected by using K_d factor

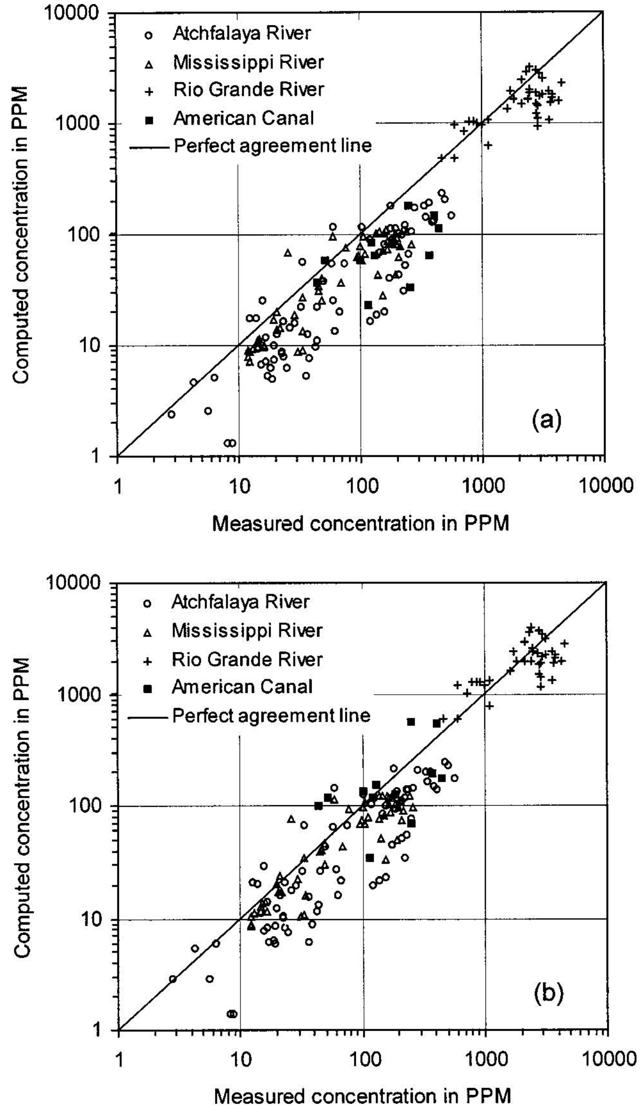

Fig. 6. Comparison between computed and measured bed-material concentration for the Engelund and Hansen Equation applied to river data: (a) based on d_{50} and (b) corrected by using K_d factor

from the small σ_g values in these two large rivers. Further improvement for these two large rivers may need to consider other flow parameters, which is beyond the scope of this paper.

Fig. 7 shows the variations of the relative median diameter defined by d_{50t}/d_{50} with the geometric standard deviation σ_g of bed material. A total of 335 data values is shown in Fig. 7, including the flume data of Einstein (1978), Einstein and Chien (1953), and Guy et al. (1966), and the field data from the Niobrara River near Cody, Nebraska (Colby and Hembree 1955), and the Middle Loup River data at Dunning, Nebraska (Hubbell and Matejka 1959). This database is limited to sand sizes with median diameter in the range of 0.104–1.039 mm, to geometric standard deviations in the range of 1.245–2.968, to flow discharges in the range of 0.019–16.06 m^3/s, to velocities in the range of 0.22–1.90 m/s, to depths in the range of 0.058–0.576 m, and to slopes in the range of 0.00023–0.0193. Table 1 presents a summary of this database.

In Fig. 7, size distribution data including the unmeasured load near the bed surface evaluated by the use of indirect methods are

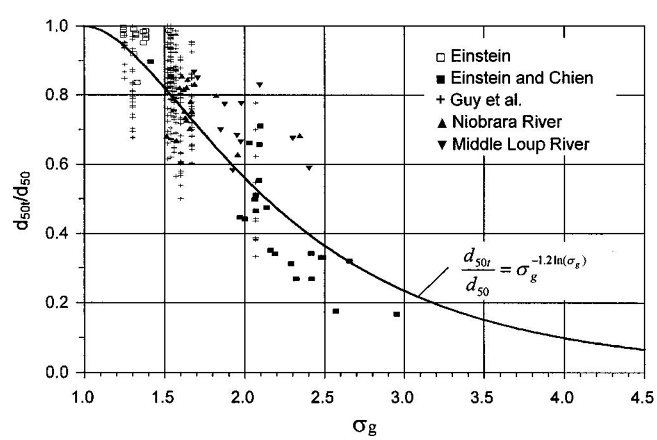

Fig. 7. Relationship between relative diameter, d_{50t}/d_{50} and geometric standard deviation, σ_g

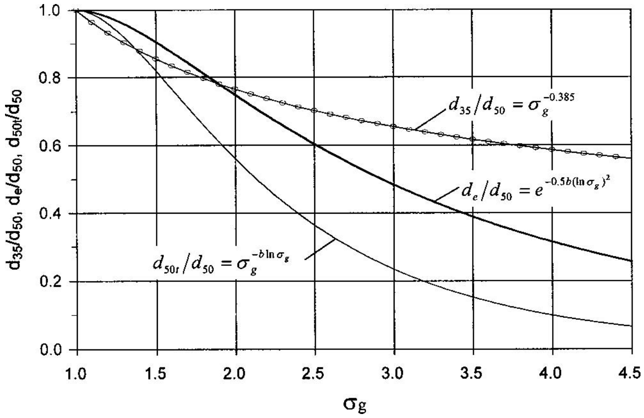

Fig. 8. Variation of d_{35}/d_{50}, d_e/d_{50}, and d_{50t}/d_{50} vs σ_g

not included. For the laboratory data, the size distributions of transported sediments were measured directly. The transported sediment size distribution data for the Niobrara River near Cody, Nebraska are obtained from measured values of suspended bed-material concentrations at a contracted section and are based on depth integrated samples. The size distribution of sediments in transport reported for the Middle Loup River at Dunning, Nebraska are measured values of suspended bed-material concentrations with a turbulence flume and are also based on depth integrated samples.

From Fig. 7 it can be seen that the value of d_{50t} is finer than the corresponding value of d_{50}, and that as σ_g increases the value of d_{50t}/d_{50} decreases. The reason is that the finer sizes in sediment mixtures are more readily transported by flow, which is commonly referred to as the selective transport of grains by flow or hydraulic sorting. It is a significant phenomenon in the transport process of nonuniform sediments.

The equation line given by Eq. (25) is plotted in Fig. 7 along with the measured data. It is seen that the measurements follow the equation line closely.

Fig. 8 is a plot showing the variation of relative diameters of d_{35}/d_{50}, d_e/d_{50} and d_{50t}/d_{50} with σ_g. It is seen that the relative diameter of d_{35}/d_{50} equals that of d_{50t}/d_{50} at $\sigma_g=1.38$ and d_e/d_{50} equals that of d_{50t}/d_{50} at $\sigma_g=1.9$. The d_{35} and d_{50t} both have values smaller than d_{50}, so the use of d_{35} or d_{50t} can give higher transport rate than based on d_{50}. However, the use of d_{35} or d_{50t} as representative size is valid only for data with σ_g values around 1.4 and 1.9, respectively.

The proposed size gradation correction factor K_d can be applied in practice for bed-material load computation in case of nonuniform sediments. The procedure is illustrated using the data measured at Tarbert Landing, Mississippi River on April 16, 1965 [$Q=24{,}468\ \text{m}^3/\text{s}$, $W=1{,}103$ m, $h=014.42$ m, $S=0.0000365$, $T=15.0°\text{C}$, $d_{35}=0.167$ mm, $d_{50}=0.199$ mm, $\sigma_g=1.648$, $C_t=136$ ppm, and $d_{50t}=0.107$ mm (from suspended load)]. The detailed procedure for applying the proposed method is as follows.

Step 1. First calculate the transport rate with d_{50} of the bed only. From the data given earlier, the bed-material concentration calculated by using the Engelund and Hansen equation is $C_{tc}=100.7$ ppm.

Step 2. Then calculate K_d and correct the calculations. According to Eq. (20) we have $K_d=e^{0.5(1.2\ \ln\ 1.648)^2}=1.20$. Applying the K_d factor gives the corrected bed-material concentration $C_{tc}=1.20\times 100.7=120.5$ ppm.

Step 3. Calculate the d_{35}, d_e, and d_{50t}.

These three characteristic sizes can be calculated from Eqs. (32), (31), and (25), respectively, and giving $d_{35}=0.164$ mm, $d_e=0.171$ mm, and $d_{50t}=0.147$ mm.

Step 4. Compare the computed results with field measurements.

It is obvious that the corrected bed-material concentration 120.5 ppm, comparing with the value of 100.7 ppm calculated by the Engelund and Hansen equation, is more close to the measured value of 136 ppm. As expected, the variable representative diameter of bed material $d_e=0.171$ mm is finer than the measured $d_{50}=0.199$ mm of bed material. The calculated value of $d_{50t}=0.147$ mm is much coarser than measurement, which may be explained by the fact that $d_{50t}=0.107$ mm is obtained from only measured suspended load and the measured value of d_{50t} for total bed-material load is not available.

Summary and Conclusions

The effects of nonuniformity of bed material on the transport of sediment mixtures are studied extensively. From the analysis, the following conclusions can be reached.

1. Sediment transport equations based on d_{50} for uniform sediments usually underestimate the transport rates for nonuniform sediment mixtures. The size gradation correction factor K_d expressed by Eq. (20) is a function of the geometric standard deviation of bed material. It is theoretically derived from the fractional transport concept based on a lognormal particle size distribution of the bed material. The use of K_d in conjunction with a sediment transport equation based on a single representative size for uniform sediments can produce more accurate predictions for nonuniform sediment mixtures. The improvement on transport rate by K_d is significant for data with σ_g greater than 2.0, while the correction is negligible for data with σ_g less than 1.5. Considering that the method was tested using both laboratory and field data in the range of 0.091–0.715 mm for d_{50}, the proposed correction factor is expected to be applicable to only sand-bed channels.
2. Similar to the bed material size distribution, the sediments in transport follow a lognormal size distribution. The median diameter of sediment in transport is generally finer than the median diameter of bed material, due to the selective transport of grains by flow. The relative median size of sediment in transport, d_{50t}/d_{50}, decreases as size gradation increases, and the relationship between them can be represented by Eq. (25).
3. A variable representative diameter d_e expressed by Eq. (31) is theoretically derived for bed materials with a lognormal distribution. The representative diameter d_e decreases as σ_g increases, resulting in a higher transport rate for nonuniform sediment mixtures. The use of d_{35} as a representative size of bed material suggested by Einstein (1944) and Ackers and White (1973) is not a generally valid value.

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Notation

The following symbols are used in this paper:

AGD = average geometric deviation between computed and measured bed-material concentrations;
b = exponent;
C = coefficient;
C_{tc}, C_{tm} = computed and measured bed-material concentrations, respectively;
d = particle size of bed material;
d_e = $1/(\Sigma\Delta P_{bi}/d_i)$, effective diameter defined by Nordin;
d_e = equivalent representative diameter defined by Molinas and Wu;
d_e = variable representative diameter of bed material;
d_i = representative diameter of bed material corresponding to the size fraction i;
d_m = mean diameter of bed material;
d_{mt} = mean size of sediment in transport;
d_p = pth percentile of the bed material size distribution;
d_s = representative diameter of bed material defined by van Rijn;
d_{50t} = median diameter of sediment in transport;
f' = friction factor defined by Engelund and Hansen;
G = size gradation coefficient of bed material;
g = gravitational acceleration;
h = flow depth;
J = total number of data sets;
K_d = size gradation correction factor;
m = exponent;
N = total number of size fractions present in a sediment mixture;
P = percentage for which the diameter of bed material is corresponding to d_{50t} for a given σ_g;
Q_s = total bed-material transport rate;
Q_{sd_e} = total bed-material transport rate obtained based on d_e;
Q_{sp} = potential bed-material transport rate;
Q_{s50} = total bed-material transport rate obtained based on d_{50};
q_t = total bed-material sediment discharge by weight per unit width;
R_j = discrepancy ratio between computed and measured bed-material concentration;
RMS = root mean square;
S = slope;
s_g = specific gravity;
T = transport stage parameter temperature;
u = dummy variable;
V = average flow velocity;
V_{ci} = the incipient velocity for a particular size class i in a mixture;
V_* = shear velocity;
V' = the absolute fluctuations of velocity;
v = dummy variable;
W = width;
x = general variable;
y = general variable;
ΔP_{bi} = fraction of bed material, by dry weight, corresponding to the size fraction i;
ΔP_{ci} = fraction of transported bedload sediments, by dry weight, corresponding to the size fraction i;
ΔP_{moi} = relative mobility of bed material corresponding to size fraction i;
γ_s, γ = specific weight of sediment and water, respectively;
ζ = general variable;
θ = dimensionless shear parameter;
μ_y = mean value of Gaussian distribution;
ξ_p = pth percentile of standard normal distribution;
σ = the standard deviation of V'/V distribution;
σ_g = standard deviation of bed material size;
σ_y = standard deviation of Gaussian distribution;
τ = shear stress along the bed;
τ' = grain shear stress;
τ_c = critical shear stress;
Φ = dimensionless sediment transport function;
ω = fall velocity corresponding to particle size d;
ω_i = fall velocity corresponding to particle size d_i;
ω_m = $(\Sigma\Delta P_{bi}\omega_i^m)^{1/m}$=defined by Han; and
ω_{50} = fall velocity of sediment corresponding particle size d_{50}.

Subscripts

i = size fraction number in a data set;
j = data set number; and
t = transport material.

References

Ackers, P., and White, W. R. (1973). "Sediment transport: New approach and analysis." *J. Hydraul. Div., Am. Soc. Civ. Eng.* 99(11), 2041–2060.

Bagnold, R. A. (1966). "An approach to the sediment transport problem from general physics." *U.S. Geological Survey Professional Paper 422-J*. U.S. Geological Survey, Washington, D.C.

Chien, N., and Wan, Z. H. (1999). *Mechanics of Sediment Transport*, ASCE Press, New York.

Colby, B. R., and Hembree, C. H. (1955). "Computations of sediment discharge, Niobrara River near Cody, Nebraska." *U.S. Geological Survey Water Supply Paper 1357*. U.S. Geological Survey, Washington, D.C.

Dou, G. R. (1974). "Similarity theory and its application to the design of total sediment transport model." *Research Bulletin of Nanjing Hydraulic Research Institute*, Nanjing, China (in Chinese).

Einstein, H. A. (1944). "Bed load transportation in Mountain Creek." *Technical Paper No. 55, Soil Conservation Service*, United States Department of Agriculture.

Einstein, H. A. (1950). "The bedload function for sediment transportation in open channel flows." *U.S. Department of Agriculture Soil Conservation Service Technical Bulletin No. 1026*.

Einstein, H. A. (1978). "Sediment transport data in laboratory flumes." *Publication Circular No. 2*, International Research and Training Center on Erosion and Sedimentation, Beijing, China.

Einstein, H. A., and Chien, N. (1953). "Transport of sediment mixtures with large ranges of grain sizes." *MRD Sediment Series No. 2*, U.S. Army Engineer Division, Missouri River, Corps of Engineers.

Engelund, F., and Hansen, E. (1967). *A Monograph on Sediment Transport in Alluvial Streams.* Danish Technical (Teknisk Forlag).

Guy, H. P., Simons, D. B., and Richardson, E. V. (1966). "Summary of Alluvial Channel data from flume experiments, 1956–1961." *U.S. Geological Survey Professional Paper 462-I*. U.S. Geological Survey, Washington, D.C.

Han, Q. (1973). "A study on non-equilibrium transport of sediment in reservoirs." *Proceedings of Reservoir Sedimentation*, Wuhan, China (in Chinese).

Hsu, S. M., and Holly, F. M., Jr. (1992). "Conceptual bed-load transport model and verification for sediment mixtures." *J. Hydraul. Eng.*

118(8), 1135–1152.
Hubbell, D. W., and Matejka, D. Q. (1959). "Investigation of sediment transportation, Middle Loup River at Dunning, Nebraska." *U.S. Geological Survey Water Supply Paper 1476.* U.S. Geological Survey, Washington, D.C.
Mahmood, K. (1973a). "Lognormal size distribution of particulate matter." *J. Sediment. Petrol.* 43(4), 1161–1166.
Mahmood, K. (1973b). "Flow in sand-bed channels." *CUSUSWASH, Water Management Technical Report No. 11*, Colorado State Univ., Fort Collins, Colo.
Meyer-Peter, E., and Müller, R. (1948). "Formula for bed load transport" *Proc. 2nd. Meeting*, Vol. 6, Stockholm, 39–64.
Misri, R. L., Garde, R. J., and Ranga Raju, K. G. (1984). "Bed load transport of coarse nonuniform sediment," *J. Hydraul. Eng.* 110(3), 312–328.
Molinas, A., and Wu, B. S. (1998). "Effect of size gradation on transport of sediment mixtures." *J. Hydraul. Eng.* 124(8), 786–793.
Molinas, A., and Wu, B. S. (2001). "Transport of sediment in large sand-bed rivers." *J. Hydraul. Res.* 39(2), 135–146.
Nordin, C. F. (1989). "Application of Engelund-Hansen sediment transport equation in mathematical models." *Fourth International Symposium on River Sedimentation*, China Ocean, Beijing, China, 611–616.
Nordin, C. F., and Beverage, J. P. (1965). "Sediment transport in the Rio Grande, New Mexico." *U.S. Geological Survey Professional Paper 462-F.* U.S. Geological Survey, Washington, D.C.
Samaga, B. R., Ranga Raju, K. G., and Garde, R. J. (1986a). "Bed load transport of sediment mixtures." *J. Hydraul. Eng.* 112(11), 1003–1018.
Samaga, B. R., Ranga Raju, K. G., and Garde, R. J. (1986b). "Suspended load transport of sediment mixtures." *J. Hydraul. Eng.* 112(11), 1019–1035.
Shen, H. W., and Rao, C. X. (1991). "Transport of uniform and nonuniform sediment sizes." *Proceedings of the Fifth Federal Interagency Sedimentation Conference*, Vol. I, U.S. Subcommittee on Sedimentation, Las Vegas, Nev. 4-162–169.
Simons, D. B. (1957). "Theory of design of stable channels in alluvial materials." PhD thesis, Colorado State Univ., Fort Collins, Colo.
Smart, G. M., and Jaeggi, M. N. R. (1983). "Sediment transport on steep slopes." Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, Nr. 64, Zürich, 1983.
Swamee, P. K., and Ojha, C. S. P. (1991). "Bed-load and suspended-load transport of nonuniform sediments." *J. Hydraul. Eng.* 117(6), 774–787.
Toffaleti, F. B. (1968). "A precedure for computation of the total river sand discharge and detailed distribution, bed to surface." *Technical Report 5*, U. S. Army Corps of Engineers Water Ways Experiment Station, Wicksburg, Miss.
van Rijn, L. C. (1984). "Sediment transport, Part II: Suspended load transport." *J. Hydraul. Eng.* 110(11), 1613–1641.
Velikanov, M. A. (1954). "Gravitational theory of sediment transport." *Journal of Science of the Soviet Union*, Geophysics, Vol. 4 (in Russian).
White, W. R., and Day, T. J. (1982). "Transport of graded gravel bed material." *Gravel-Bed Rivers, Fluvial Processes, Engineering and Management*, edited by R. D. Hey, J. C. Bathurst, and C. R. Thorne, Wiley, New York, 181–223.
Wu, B. S. (1999). "Fractional transport of bed-material load in sand-bed channels ." PhD dissertation, Department of Civil Engineering, Colorado State Univ., Fort Collins, Colo.
Zhang, R. J. (1959). "A study of the sediment transport capacity of the middle and lower Yangtze River." *J. Sediment Res.*, Beijing, 4(2) (in Chinese).
Zhang, R. J., and Xie, J. H. (1993). *Sedimentation Research in China, Systematic Selections.* China Water and Power, Beijing.