Formulas for Sediment Porosity and Settling Velocity

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Abstract: Several existing formulas for the initial porosity and settling velocity of sediment have been tested by using extensive data collected from different countries and regions, and modified to achieve better reliability or convenience in use.

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Introduction

Sediment transport in rivers has been extensively studied since the early 20th century. Scientists and engineers have established theories and methodologies to give answers or solution methods for many important problems, such as quantification of sediment properties, determination of sediment transport rate under certain flow conditions, prediction of river morphological changes, etc. However, it is very hard for engineers to make a decision when several available empirical methods give different answers for the same problem. Thus, a review of the existing methods becomes necessary. Importantly, many empirical formulas were established decades ago based on a limited number of experimental and field data. Many new or rediscovered old data sets from different countries and regions may be used to enhance the reliability and accuracy of these established formulas and methods. With this intention, the authors have revisited two classical problems: initial porosity of sediment deposits and settling velocity of sediment particles. Several existing formulas have been tested by using the data collected from different sources, and newly modified formulas with more reliability and/or convenience have been proposed.

Initial Porosity of Sediment Deposits

The initial porosity of sediment deposits has been investigated by Hembree et al. (1952), Lane and Koelzer (1953), Colby (1963), Komura (1963), and Han et al. (1981). For the sediment deposits of one year or less, Komura (1963) related the porosity to the median diameter as

$$p'_m = 0.245 + \frac{0.0864}{(0.1d_{50})^{0.21}} \tag{1}$$

where p'_m=initial porosity of sediment deposit; and d_{50}=median diameter of sediment mixture (in millimeters).

Han et al. (1981) proposed the following semiempirical formula to calculate the initial porosity of uniform sediment deposits:

$$p'_m = \begin{cases} 1 - 0.525\left(\dfrac{d}{d+4\delta_1}\right)^3 & d < 1\ \text{mm} \\ 0.3 + 0.175e^{-0.095(d-d_0)/d_0} & d \geq 1\ \text{mm} \end{cases} \tag{2}$$

where d=size of sediment (in millimeters); d_0=reference size (set as 1 mm); and δ_1=thickness of the water layer attaching to sediment particles, approximately set as 0.0004 mm.

As shown in Fig. 1, the authors revalidated the relationship between the initial porosity and the sediment size using more extensive data, including the laboratory data of Trask (1931) and Straub (1935) as well as the field data in Lake Clarmore, Moran Reservoir, Neosha County State Lake, Lake Marinuka, Tongue River Reservoir, and Powder River (Hembree et al. 1952), Lake Mead, Tone River, Pigeon Point Shelf, Nagara River, and Hatori Dam (Komura 1963), Sanmenxia Reservoir, Danjiangkou Reservoir, and another seven reservoirs in China (see CAHE Committee on Sedimentation 1992). The dry density, ρ'_s, in Fig. 1 is calculated from the porosity by using

$$\rho'_s = (1 - p'_m)\rho_s \tag{3}$$

where ρ_s=sediment density having a value of 2.65 t/m^3. Note that the international (SI) units are used here. It can be seen that Komura's formula is quite close to the trend of the data sets, slightly underestimating the dry density for sand and gravel and overestimating for silt and coarse clay. The semiempirical formula of Han et al. (1981) has significant errors, perhaps due to the fact that their formula was developed only for uniform-size sediment deposits. To match the measured data better, Komura's formula (1) is modified as

$$p'_m = 0.13 + \frac{0.21}{(d_{50} + 0.002)^{0.21}} \tag{4}$$

where d_{50} is in millimeters.

Compared with the measured data in Fig. 1, the mean relative errors of Eq. (4), Komura's formula and Han et al.'s formula are 12.7, 14.1, and 21.5%, respectively. The mean relative error is defined as $[(\sum_{i=1}^{m}|f_{\text{cal},i} - f_{\text{meas},i}|)/f_{\text{meas},i}]/m$, with m=number of

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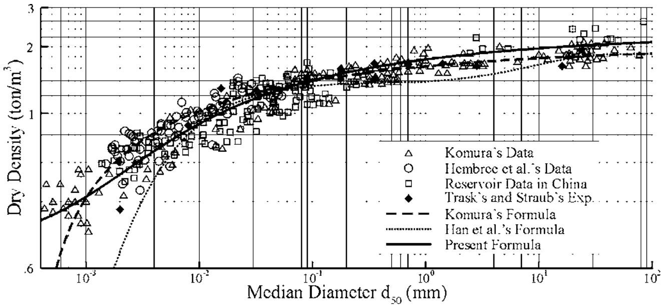

Fig. 1. Dry density of sediment deposit as function of d_{50}

samples, $f_{\mathrm{meas},i}$=measured value, and $f_{\mathrm{cal},i}$=predicted value. The porosities predicted by Eq. (4), Komura's formula, and Han et al.'s formula for 95.0, 87.3, and 77.8% of the samples, respectively, are within 30% error from the measured values. The modified formula (4) performs best.

Note that formula (4) is only for the initial porosity of sediment deposits. It does not consider the variation of deposit porosity with time and along depth due to the consolidation, especially for fine sediments (Lane and Koezler 1953), and the difference due to the effects of bed forms, organic matters (e.g., microalgae), etc. (Wheatcroft 2002).

Settling Velocity of Sediment Particles

Previous Studies

The terminal settling velocity of sediment particles, ω_s, can be derived by equating the effective weight force to the drag resistance as

$$\omega_s^2 = \frac{4}{3C_d}\frac{\rho_s - \rho}{\rho}gd \tag{5}$$

where ρ=water density; g=gravitational acceleration; and C_d=drag coefficient.

In 1851 Stokes solved the Navier–Stokes equations with the aid of a shear function and neglecting all inertia terms, and theoretically derived the drag coefficient for a spherical particle in the streamline settling region ($\mathsf{R}<0.5$)

$$C_d = \frac{24}{\mathsf{R}} \tag{6}$$

where R=particle Reynolds number, defined as $\mathsf{R}=\omega_s d/\nu$, with ν being the kinematic viscosity of water. Oseen (1927) and Goldstein (1929) included more inertia terms in the Navier–Stokes equations and derived more complete analytical solutions that extend the application range a little further but are still in a limited range of Reynolds number ($\mathsf{R}<2$). For higher R, the drag coefficient has to be determined by experiments. Rouse (1938) and Brown and Lawler (2003) summarized the available data and presented typical relations of $C_d-\mathsf{R}$ for spherical particles.

Because the particle shape and surface roughness affect the settling process, the $C_d-\mathsf{R}$ curve of natural sediment particles deviates from that of spheres. Rubey (1933), Cancharov [see Cheng 1997], Interagency Committee (1957), Zhang (1961), Sha (1965), Graf (1971), Zanke (1977), Hallermeier (1981), Van Rijn (1989), Raudkivi (1990), Julien (1995), Cheng (1997), and Ahrens (2000, 2003) have developed empirical or semiempirical relations for the settling velocity of sediment particles. Generally, the drag coefficient can be approximated as (Cheng 1997)

$$C_d = \left[\left(\frac{M}{\mathsf{R}}\right)^{1/n} + N^{\frac{1}{n}}\right]^n \tag{7}$$

Table 1. Values of M, N, and n

Formula	Rubey (1933)	Zhang (1961)	Van Rijn (1989)	Raudkivi (1990)	Julien (1995)	Cheng (1997)
M	24	34	24	32	24	32
N	2.1	1.2	1.1	1.2	1.5	1
n	1	1	1	1	1	1.5

where M, N, and n=coefficients. Table 1 shows the values of these three coefficients given by different investigators in the case of naturally worn sediment particles, the shape factor of which usually is about 0.7. The coefficient M was given a value of 24 by Rubey (1933), Van Rijn (1989), and Julien (1995), and values between 32 and 34 by Zhang (1961), Raudkivi (1990), and Cheng (1997). The tests against measurement data performed by Cheng (1997) have shown that for natural sediment the values of 32–34 for M give better predictions than the value of 24. The latter corresponds to the Stokes' law, Eq. (6) for spherical particles. Rubey (1933) gave the coefficient N a value of 2.1, which yields a significant underestimation for the settling velocity of coarse sediment particles.

Krumbein (1942), Corey (1949), McNown et al. (1951), Wilde (1952), and Schulz et al. (1954) experimentally investigated the effect of sediment particle shape on the settling velocity, and the Subcommittee on Sedimentation of the U.S. Interagency Committee on Water Resources (Interagency Interagency Committee (1957) summarized the data measured by these investigators and published a graphical relation of the drag coefficient with sediment size, water temperature, and shape factor. This graphical relation has unique merits because it has considered the effect of particle shape on sediment settling that is ignored in many other popular formulas mentioned above. However, this graphical relation consists of a series of curves and tables, and several interpolations must be conducted to obtain the sought solution. It is not convenient to use. In addition, all the data used in the calibration were in the range of $\mathsf{R}>3$, and the relation was extended in the range of $\mathsf{R}<3$ based on the assumption that it approaches the Stokes' law Eq. (6) for spheres. Many experiments have shown that the settling velocity of fine sediment particles ($\mathsf{R}<1$) somehow deviates from the Stokes' law Eq. (6) of spheres.

Romanovskii (1972) also performed experiments to investigate the effect of sediment particle shape on settling velocity, and obtained a formula of the settling velocity in the turbulent settling region. In Romanovskii's formula, the particles size was defined as $d_{\mathrm{cp}}=(a+b+c)/3$ and the shape factor was $\Theta=d_{\mathrm{cp}}^2/(ab)$, in which a, b, and c=lengths of the longest, intermediate, and shortest axes of the particle. Dietrich (1982) proposed an empirical formula to determine the settling velocity of sediment from laminar to turbulent settling regions, considering the effects of sediment size, density, shape factor, and roundness factor. However, the Powers roundness factor used in Dietrich's formula is rarely measured in practice, and his formula is very complicated and relatively difficult to use. Jimenez and Madson (2003) derived a simple formula from the relation of Dietrich. Jimenez and Madsen's formula determines the settling velocity of sediment particles when the shape and roundness factors are known, but two coefficients in their formula are still graphically related to the shape

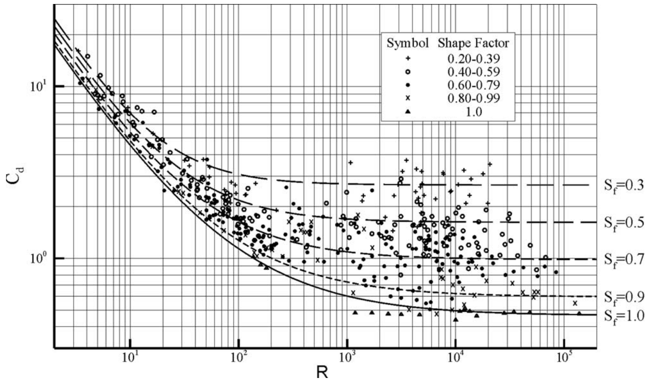

Fig. 2. Drag coefficient as function of Reynolds number and particle shape

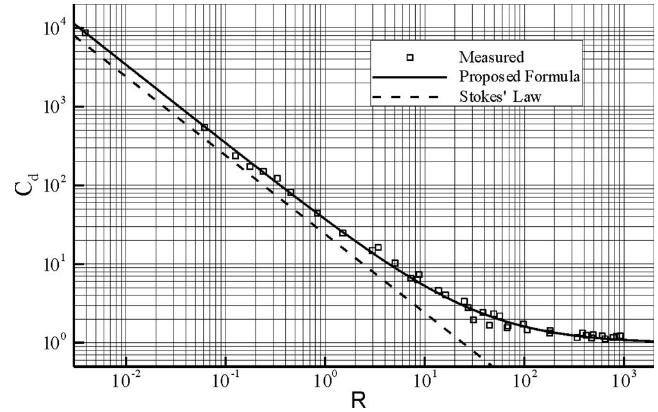

Fig. 3. Drag coefficient as function of Reynolds number for natural sediment (S_f=0.7)

factor. Swamee and Ojha's (1991) proposed formulas to represent Schulz et al.'s (1954) graphical relations of C_d–R for natural and crushed particles. Since the C_d–R curves of Schulz et al. have been replaced by the curves recommended by the Subcommittee on Sedimentation of the U.S. Interagency Committee on Water Resource (Interagency Committee 1957), Swamee and Ojha's (1991) formulas are less favorable. In addition, Gogus et al. (2001) experimentally studied the settling of angular particles and proposed a new factor to represent sediment particle shape. Because the range of the data used is very narrow, Gogus et al.'s finding still needs to be verified.

New Development

In this study, we have reevaluated the relation recommended by the U.S. Interagency Committee using a wider range of data and used Eq. (7) to replace the graphical relation. The data for the settling of natural sediment particles measured by Krumbein (1942), Corey (1949), Wilde (1952), Schulz et al. (1954), and Romanovskii (1972) are used. The sediment size is represented by the nominal diameter in the present analysis. For Romanovskii's data, the nominal diameter is approximated as $d=\sqrt[3]{abc}$, and only the data for coarse particles ($\mathsf{R}>1{,}000$) are used due to lack of water temperature record. Based on these five groups of data, the coefficients M, N, and n in Eq. (7) are calibrated as

$$M = 53.5e^{-0.65S_f}; \quad N = 5.65e^{-2.5S_f}; \quad n = 0.7 + 0.9S_f \qquad (8)$$

where S_f=Corey shape factor defined as $c/\sqrt{ab}$.

Fig. 2 shows a comparison between the measured drag coefficients and those calculated using Eq. (7) with the coefficients given by Eq. (8). Because the data included in Fig. 2 are in the range of $\mathsf{R}>3$, the trend of the C_d–R relation in the range of $\mathsf{R}<3$ is determined by using the data of Russian scientists Zegzhda (1934), Arkhangel'skii (1935), and Sarkisyan (1958) compiled by Cheng (1997). The Corey shape factor of the sediment used in these three experiments is assumed to be 0.7, as suggested by Cheng (1997). For this value of shape factor, Eq. (8) corresponds to M=33.9, N=0.98, and n=1.33, which are in the ranges presented in Table 1. The relationship between C_d and R in the range of these data is shown in Fig. 3.

It should be noted that when S_f=1.0 the proposed Eq. (8) prescribes a C_d–R curve that deviates from the relation of spheres obtained by Rouse (1938). The reason is that the naturally worn sediment particles with a Corey shape factor of 1.0 may not be spheres and the particle angles and surface roughness also affect the settling process.

Inserting Eq. (7) into Eq. (5), one can derive the general relation of settling velocity as

$$\omega_s = \frac{M\nu}{Nd}\left[\sqrt{\frac{1}{4}+\left(\frac{4N}{3M^2}D_*^3\right)^{1/n}}-\frac{1}{2}\right]^n \qquad (9)$$

where $D_*=d[(\rho_s/\rho-1)g/\nu^2]^{1/3}$; and d=nominal diameter of sediment particles.

Eq. (9) is applied with the coefficients M, N, and n determined by Eq. (8). It is an explicit relation of the settling velocity for given sediment size and shape factor so that it can be easily used.

Comparison with Existing Methods

The predictions using Eq. (9) and the curves recommended by the U.S. Interagency Committee (1957) have been compared in Fig. 4. Here, the temperature is 24°C, the Corey shape factor is in the range of 0.3–0.9, and the sediment size is between 0.2 and 64 mm. It can be seen that these two methods give very close predictions. The average deviation between them is about 2.75%. However, a bigger deviation between these two methods is expected for fine sediment (less than 0.2 mm in diameter). The rea-

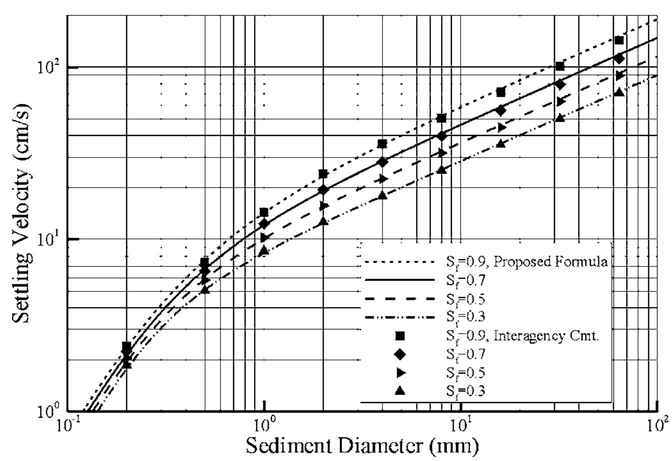

Fig. 4. Comparison of Eq. (9) and relation of Interagency Interagency Committee (1957)

Table 2. Comparison of Different Formulas against Data with Shape Factor

Data range	Data number	Mean relative errors (%)			
		Dietrich (1982)	Swamee and Ojha's (1991)	Jimenez and Madson (2003)	Wu and Wang (present)
Fine sediment ($D_* < 30$)	289	7.7	12.4	8.1	8.1
Coarse sediment ($D_* \geq 30$)	282	14.2	13.3	13.3	10.1
Total	571	10.9	12.8	10.7	9.1

son, which has been mentioned above, is that the Interagency Committee's curves approach the Stokes' law Eq. (6) that might have 30% error for the settling velocity of natural sediment particles as shown in Fig. 3. The present formula (9) has been validated by using the measurement data and should have better accuracy than the Interagency Committee's curves for fine sediment particles.

The newly proposed formula (9) has been also compared with those of Dietrich (1982), Swamee and Ojha's (1991), and Jimenez and Madson (2003), which all consider the effect of particle shape on the sediment settling. A total of 571 measurement data sets, including those in Fig. 2 and reported by Briggs et al. (1962), are used to test the four formulas. Briggs et al.'s data, which were for heavy mineral sands, were used to calibrate Dietrich's formula but not included in Fig. 2. Because the particle roundness information is not known in the data sets, a value of 3.5 is used for the Powers roundness index required in Dietrich's and Jimenez and Madsen's formulas. Table 2 shows the mean relative errors of the four compared formulas. The mean relative errors are 9.1, 10.7, 10.9, and 12.8% for the newly proposed formula, Jimenez and Madsen's formula, Dietrich's formula, and Swamee and Ojha's formula, respectively. Dietrich's formula gives slightly better prediction for fine sediment but worst prediction for coarse sediment. The newly proposed formula somehow performs better than the three existing formulas on average.

In the case where the sediment particle shape is not measured, the newly proposed formula (9) can be still used for naturally worn sediment particles by assuming the Corey shape factor as 0.7 (Interagency Committee 1957; Dietrich 1982; Cheng 1997) and setting the coefficients $M=33.9$, $N=0.98$, and $n=1.33$. This formula has been compared with nine existing formulas listed in Table 3 against the Russian data shown in Fig. 3, Hallermeier (1981) data, and Raudkivi (1990) data. Forty-three sets of Russian data and 13 sets of Raudkivi's data are taken from Cheng (1997). Because many of the data compiled by Hallermeier (1981) lack information on temperature or sediment density, only 44 sets of these data restricted for quartz sands (with a specific gravity of about 2.65) are selected. The sediment size in the Hallermeier's data is characterized by the sieve diameter, which is approximately converted to the nominal diameter by dividing by a factor of 0.9 (Raudkivi 1990). There are 100 data sets in total. All these data are for naturally worn sediment, assumed to have a Corey shape factor of 0.7 and a Powers roundness index of 3.5. Table 3 shows the mean relative errors of the ten compared formulas. It can be seen that the formula of Swamee and Ojha's (1991) has significant error, which occurs mainly for fine sediment particles ($d < 0.1$ mm). Rubey's (1933) formula and Van Rijn's (1989) formula also have large errors. The six formulas of Zhang (1961), Hallermeier (1981), Dietrich (1982), Cheng (1997), Ahrens (2000), and Jimenez and Madson (2003) perform well and have very close accuracies. The newly proposed formula predicts slightly better than these six formulas.

Conclusions

The formulas proposed by Komura (1963) and Han et al. (1981) for the initial porosity of sediment deposits have been tested using numerous data collected from different countries and regions. It is found that Komura's formula slightly underestimates the dry density for sand and gravel and overestimates for silt and coarse clay. Han et al.'s semiempirical formula, which was developed for uniform-size sediment mixture, exhibits more errors in comparison with the collected data. The coefficients in Komura's formula have been recalibrated by using the extended data set.

The relationship of the settling velocity with particle size and shape recommended by the Subcommittee on Sedimentation of the U.S. Interagency Committee on Water Resources (Interagency Committee 1957) has been reanalyzed. The original curves and tables are replaced by an explicit mathematical expression for the settling velocity that can be used more conveniently. The proposed formula has been tested by using not only the data used by the Interagency Committee, but also the data from other different sources. For the sediment particles coarser than 0.2 mm, the proposed formula has almost the same accuracy as the original curves recommended by the Interagency Committee. For the sediment finer than 0.2 mm, the proposed formula should have better accuracy than the original curves because it has been calibrated by using the measurement data rather than by the assumption that it approaches the Stokes' law of spheres. The proposed formula also exhibits better performance than nine existing formulas in the literature.

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Table 3. Comparison of Different Formulas against Data without Shape Factor

Formula	Rubey (1933)	Zhang (1961)	Hallermeier (1981)	Dietrich (1982)	Van Rijn (1989)	Swamee and Ojha's (1991)	Cheng (1997)	Ahrens (2000)	Jimenez and Madson (2003)	Wu and Wang (present)
Mean relative error (%)	20.5	8.5	8.7	8.2	19.3	45.0	7.4	7.6	7.9	6.8

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