Rui-Jin Zhang's Research on Sediment Transport

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Introduction

The rivers in China convey about 5% of the global water runoff, but carry about 30% of the global sediment load. Especially, the Yellow River in China has the highest sediment concentration among the major rivers all over the world. This has created a great challenge to Chinese scientists and engineers of many generations, who have to find feasible and sustainable solutions to the sedimentation problems, and thus, have made substantial and systematic advancements on sediment research in the last century. Among the internationally well-known Chinese scientists like Ning Chien (1922–1986) or Bingnan Lin (1920–2014), Rui-Jin Zhang (1917–1998) was one of the most distinguished leading scientists in sediment research. Zhang's work involved almost every aspect of sedimentation engineering, and particularly made significant contributions on sediment settling velocity, incipient velocity, concentration distribution, transport capacity, bed forms, hyperconcentrated flow, reservoir sedimentation, and river restoration. To the authors' knowledge, Zhang's formulas of sediment settling velocity and transport capacity are as reliable as many recently developed formulas and are still very useful (Fang and Wang 2000; Wu 2007; Dey 2014). Because Zhang published his research findings and practice experiences mainly in Chinese literature, the aim of this forum paper is to highlight Zhang's studies on sediment transport and share some of his theories and formulas with the international hydraulic engineering community. The forum paper also pays a tribute to the centennial anniversary of Rui-Jin Zhang.

Biography of Rui-Jin Zhang

Rui-Jin Zhang was born on January 15, 1917 in a Badong village of Hubei Province, which is located near the recently-built Three Gorges Dam on the Yangtze River, China. In 1939, he graduated in civil engineering from Wuhan University, China. He explored the problems of river sedimentation and regulation in his thesis, which was entitled "*Comparative study on the plan of route regulation for the Yongding River and planning of flood control for the Mississippi River in the USA*." It was exceptionally written in English, although most theses were written in Chinese in that time. After graduation, he was attached to the aviation mechanics group at the School of Engineering, National Central University in Chongqing for half a year, and then worked at the Central Water Conservancy Laboratories in Chongqing and Nanjing. He was engaged in advanced studies at the Bureau of Reclamation of the United States from May 1945 to July 1946. Zhang returned to China in 1947 and joined the Wuhan University as a faculty (Fig. 1). He served as the Vice Provost of Wuhan University, the Associate Dean of the School of Engineering, and the Dean of the School of Hydraulic Engineering. After the reorganization of the colleges and departments of Wuhan University in 1954, he was appointed as a Vice President of the Wuhan Institute of Hydraulic and Electric Engineering, and then became the President in 1978 and Honorary President in 1983. Zhang passed away in 1998 at the age of 81 years.

Zhang had a long-term commitment to sediment research. Zhang (1947) collected and analyzed a large number of sediment samples from Guanzhong, Baohui Canal, Huayuankou, and other sources and determined the sediment load of the Yellow River as around 1.5 billion tons per year. This amount is quite close to recent estimates using newer measurements. Zhang (1950) modified the Rouse (1937) equation for the distribution of suspended sediment concentration in turbulent flow. The modified equation fits well with the measured data and overcomes the defect of the Rouse equation, which gives an unrealistic zero sediment concentration at the free surface. Zhang (1961) proposed an equation for the

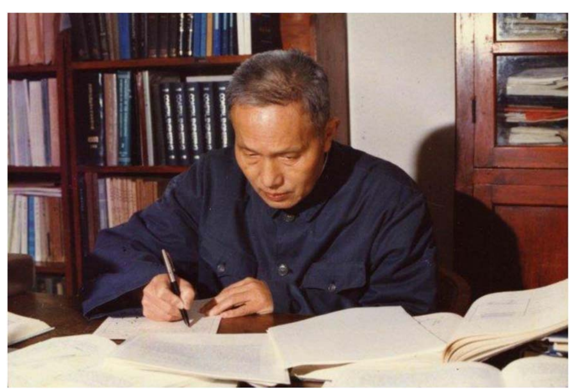

Fig. 1. Zhang in his office at Wuhan University. (Image by Guangming Tan.)

terminal settling velocity of sediment particles, which is applicable in the laminar, transitional, and turbulent flow regimes. He developed a unified formula for the critical velocity of incipient motion of both noncohesive and cohesive sediment particles by analyzing the forces acting on a sediment particle on the bed surface.

Zhang (1957, 1963) carried out a systematic review of the gravitational theory of suspended-load transport proposed by the Russian scientist Velikanov (1955, 1958). The review motivated him to propose a hypothesis that the suspended sediment particles damp the turbulence in sediment-laden flow. It led him to develop a formula for the suspended-load transport capacity (Zhang 1959, 1961), which has been extensively used in sedimentation engineering in China. This achievement was honored with an award in the 1978 National Science Conference. Zhang was one of the earlier scholars who studied hyperconcentrated flow. He conducted laboratory experiments and field investigations in the Yellow River basin, and contributed understanding of the different mechanisms of hyperconcentrated and low-concentrated sediment-laden flows (Zhang 1978, 1979a, b). He proposed an index for the distorted scale river model, which improves the theoretical basis of river modeling and allows modeling sediment transport on movable beds using different scales in the vertical and horizontal directions (Zhang 1980, 1983). He also studied the structures of helical flow in a curved channel and the effects on the channel meandering process (Zhang 1964; Zhang and Xie 1980).

Besides the theoretical research on sediment transport, Zhang was also involved in the solution of many important sedimentation engineering problems in China. In the 1960s, he participated as the deputy leader of the planning group in the planning work of Yellow River regulation, which has been the highest priority of the Chinese government agencies in the last centuries. In the 1970s, during the design of the Gezhouba Dam downstream of the Three Gorges on the Yangtze River, he proposed an approach to solving the problem of sediment deposition in the approach channels upstream and downstream of the ship lock. Through his approach, ships pass the approach channels in still water conditions and the deposited sediment is flushed by flowing water discharged from sediment-flushing gates (Zhang 1975, 1981, 1982; Zhang and Xie 1981). This approach has now been well accepted in the design of navigation channels associated with large dams in China. In 1985, the navigation channel project of the Gezhouba Dam was awarded a grand prize for the National Science and Technology Advancements by the Chinese government. In the early 1980s, Zhang was the leader of the coordination group for the study of sediment problems in the Three Gorges Project on the Yangtze River (Zhang et al. 1989).

In addition, Zhang made a great contribution to engineering education in China. He was one of the founders of the Wuhan University of Hydraulic and Electric Engineering (now merged back into Wuhan University), where he launched an undergraduate major on River Sedimentation and Regulation, which still continues today. It is a unique undergraduate curriculum all over the world, and has educated thousands of sedimentation engineering graduates. He supervised many graduate students in M.S. and Ph.D. levels. He edited or coedited several text books in Chinese, including *River Dynamics* (Zhang 1961), *River Sedimentation Engineering* (Xie et al. 1981), and *River Sediment Dynamics* (Zhang et al. 1998). He also coauthored a reference book *Sedimentation Research in China* (Zhang and Xie 1993), which was written in English.

Zhang's Formula of Sediment Settling Velocity

Settling or fall velocity is the average terminal velocity that a sediment particle attains in the settling process in quiescent, distilled water. It is one of the key parameters for sediment transport. Zhang (1961) developed a particle settling velocity formula, which is presented in this section with a brief literature review of this parameter.

The settling particle experiences the gravity, buoyancy, and drag forces. The gravity and buoyance forces are combined as the submerged weight, W, as

$$W = a_0 \Delta \rho g d^3 \tag{1}$$

where d = particle diameter; g = gravitational acceleration rate; $\Delta = \rho_s/\rho - 1$; ρ = mass density of water; ρ_s = mass density of sediment; and a_0 = coefficient related to the particle volume, for a sphere, $a_0 = \pi/6$.

The drag force, F_d, is usually written as

$$F_d = \frac{1}{2} \rho C_D a_1 d^2 w_s^2 \tag{2}$$

where C_D = drag coefficient; w_s = settling velocity; and a_1 = coefficient related to the projection area of the particle normal to the settling direction, for a sphere, $a_1 = \pi/4$.

In the terminal settling stage, the force equilibrium $W = F_d$ yields the following equation for the settling velocity:

$$w_s = \left(\frac{2a_0}{a_1 C_D} \Delta g d \right)^{1/2} \tag{3}$$

The state of the flow around the settling particle is related to the particle Reynolds number, $\mathsf{R} = w_s d/\nu$. Here, ν is the kinematic viscosity of water. When $\mathsf{R} < 1$, the flow is laminar, and Stokes (1851) derived the drag coefficient of a spherical particle as

$$C_D = \frac{24}{\mathsf{R}} \tag{4}$$

When R is larger than about 1,000, the flow around the settling particle becomes turbulent. In this regime, C_D is independent of R and is almost constant at about 0.45 for sphere (Rouse 1938). In the transitional regime between the laminar and turbulent settling, C_D varies with R and is represented by measured data without an analytical solution (Rouse 1938). A single equation that is applicable for all the laminar, transitional, and turbulent settling regimes is desirable. In addition, natural sediment particles usually are not spherical, and thus, the aforementioned drag coefficient relations may not be valid for natural sediment particles.

Rubey (1933) was the first scientist who derived a formula to cover all the three settling regimes of natural sediment particles. His formula is written as

$$w_s = F \sqrt{\left(\frac{\rho_s}{\rho} - 1 \right) g d} \tag{5}$$

where $F = 0.79$ for particles larger than 1 mm settling in water with temperatures between 10 and 25°C. For smaller grain sizes, F is determined by

$$F = \left[\frac{2}{3} + \frac{36\nu^2}{g d^3 (\rho_s/\rho - 1)} \right]^{1/2} - \left[\frac{36\nu^2}{g d^3 (\rho_s/\rho - 1)} \right]^{1/2} \tag{6}$$

Zhang (1961) considered that the drag force in the transitional settling regime is a combination of those in the laminar and turbulent regimes as follows:

$$F = k_1 \rho \nu d w_s + k_2 \rho d^2 w_s^2 \tag{7}$$

where k_1 and k_2 = weighting coefficients. The first term on the right-hand side of Eq. (7) is derived by inserting Eq. (4) into

Eq. (2), and represents the drag force in the laminar settling regime. The last term represents the drag force in the turbulent settling as expressed in Eq. (2) with a constant drag coefficient.

Equating Eqs. (1) and (7), Zhang (1961) obtained the following single formula that can cover all three settling regimes:

$$w_s = \sqrt{\left(13.95\frac{\nu}{d}\right)^2 + 1.09\Delta g d} - 13.95\frac{\nu}{d} \quad (8)$$

Note that the nominal diameter of sediment particles is used in Eq. (8). The coefficients in Eq. (8) were calibrated by using measurement data obtained by Russian scientists B. A. Arkhangel'skii, A. P. Zegzhda, D. N. Lapshin, and several other sources (Zhang 1961).

Comparing Eqs. (2) and (7), one can find that Eq. (7) is equivalent to the following relation:

$$C_D = \frac{M}{\mathsf{R}} + N \quad (9)$$

where M and N are two coefficients. Their values are $M = 24$ and $N = 0.45$ for a sphere. For natural sediments, Zhang's calibrated coefficients in Eq. (8) gave $M = 34$ and $N = 1.2$. These values are very close to the values of $M = 32$ and $N = 1.2$ obtained by Raudkivi (1990). In Rubey's (1933) formula, Eq. (6) corresponds to $M = 24$ and $N = 2.0$, and Eq. (5) is equivalent to $N = 2.1$. Zanke (1977) and Soulsby (1997) developed formulas similar to Eq. (8) with coefficients equivalent to $M = 24$ and $N = 1.1$.

For more general cases, Cheng (1997), Wu and Wang (2006), and Camenen (2007) used the following relation:

$$C_D = \left[\left(\frac{M}{\mathsf{R}}\right)^{1/r} + N^{1/r}\right]^r \quad (10)$$

where r = coefficient. When $r = 1$, Eq. (10) reduces to Eq. (9). Cheng (1997) used $M = 32$, $N = 1$, and $r = 1.5$. Wu and Wang (2006) found that these three coefficients are functions of the Corey shape factor SF. For average conditions ($SF = 0.7$), Wu and Wang (2006) gave $M = 33.9$, $N = 0.98$, and $r = 1.33$. Camenen (2007) related these coefficients to the shape and roundness factors. For average conditions ($SF = 0.7$ and a roundness factor $P = 3.5$), Camenen (2007) gave $M = 24.6$, $N = 0.987$, and $r = 1.534$.

Note that M is about 24 in the formulas of Rubey (1933), Zanke (1977), Soulsby (1997), and Camenen (2007), whereas $M = 32$–34 in the formulas of Zhang (1961), Raudkivi (1990), Cheng (1997), and Wu and Wang (2006). The formulas using $M = 24$ reduce to the Stokes' law for the laminar settling of spherical particles. Strictly speaking, the Stokes' law expressed in Eq. (4) is not accurate for nonspherical particles (McNown et al. 1950). The different M values used might be attributed to the difference between the nominal and fall diameters. The fall diameter of fine sediment particles is usually calculated from the measured settling velocity by using the Stokes' law for spheres. In other words, if the fall diameter is used, the Stokes' law in Eq. (4) can be used for natural sediment particles. If the nominal diameter is used, the Stokes' law has errors. Comparing Eqs. (4) and (9) with $M = 32$–34 in the laminar settling regime, the fall diameter is about 0.85 times the nominal diameter (Wu 2017). Therefore, the formulas of Rubey (1933), Zanke (1977), Soulsby (1997), and Camenen (2007) overestimate the settling velocity of fine sediment particles, if the nominal diameter is used.

In the turbulent settling regime, most of the aforementioned formulas give $N = 1.0$–1.2 for natural sediment particles, whereas the Rubey (1933) formula uses $N = 2.1$. The Rubey formula significantly underestimates the settling velocity of coarse particles.

In addition, Hallermeier (1981), Ahrens (2000), and Guo (2002) related the particle settling velocity to different functions of particle size, whereas Dietrich (1982) and Jimenez and Madsen (2003) related the settling velocity to the particle size, shape, and roundness. These formulas cannot be written in the form of Eq. (9) or (10), but they cover all three settling regimes. Their details are not presented here due to the paper length limit.

Wu and Wang (2006) used a total of one hundred data sets to test nine of the aforementioned formulas: Rubey (1933), Zhang (1961), Zanke (1977), Hallermeier (1981), Dietrich (1982), Cheng (1997), Ahrens (2000), Jimenez and Madsen (2003), and Wu and Wang (2006). The Zhang's (1961) formula performs as well as the later developed formulas of Hallermeier (1981), Dietrich (1982), Cheng (1997), Ahrens (2000), Jimenez and Madsen (2003), and Wu and Wang (2006). The average error of the Zhang's (1961) formula is 8.5% of the measured values, and is very close to the least average error of 6.8% obtained by the Wu and Wang (2006) formula among all the compared formulas.

The Zhang's (1961) formula of particle settling velocity has been widely used not only in China, but also in other countries. For example, it is used in the sediment transport capacity formula of Wu et al. (2000), and the CCHE1D and CCHE2D sediment transport models developed by the National Center for Computational Hydroscience and Engineering, the University of Mississippi (Wu and Vieira 2002; Wu 2001). It is included in the books of Wu (2007) and Dey (2014). These models and books are distributed worldwide.

The Zhang's (1961) formula had sound physical insight and reliable calibration. Especially, it is one of the earliest formulas that recognize the inaccuracy of the Stokes' law in the laminar settling regime of natural sediment particles, cover all three settling regimes, and are still widely used in engineering practices.

Zhang's Formula of Sediment Transport Capacity

Sediment transport capacity, or sediment-carrying capacity of flow, is defined as the amount of sediment transported for a given flow and boundary conditions, which includes the bed-load and suspended-load transport rates (Chien and Wan 1999). There are dozens of sediment transport capacity formulas in literature, including Meyer-Peter and Müller (1948), Dou (1964), Yalin (1972), and Engelund and Fredsøe (1976) for bed load; Velikanov (1958) and Zhang (1961) for suspended load; Einstein (1950), Bagnold (1966), van Rijn (1984a, b), and Wu et al. (2000) for separate bed load and suspended load; and Engelund and Hansen (1967), Ackers and White (1975), Yang (1973), Karim (1998), and Molinas and Wu (2001) for bed-material load (sum of bed load and suspended load). These formulas are based on physical principles (mass and energy conservation), dimensional analyses, and/or laboratory/field measurements, using velocity, shear stress, or stream power as the flow parameter. Details of these formulas are given in the corresponding references, and reviews can be found in Chien and Wan (1999), Wu (2007), Dey (2014), and other sources. The development and application of the Zhang's (1959, 1961) formula are described here.

In 1942, Zhang observed that erosion occurred when the discharge was less than the designed value in the irrigation channels in Shanxi Province, China. Later, he found that the reason was attributed to a large difference between the actual and designed values of Manning roughness coefficient n. This motivated him to study the effects of sediment concentration on flow resistance and energy loss. He proposed a hypothesis that the suspended sediment has a damping effect on the turbulence intensity in sediment-laden

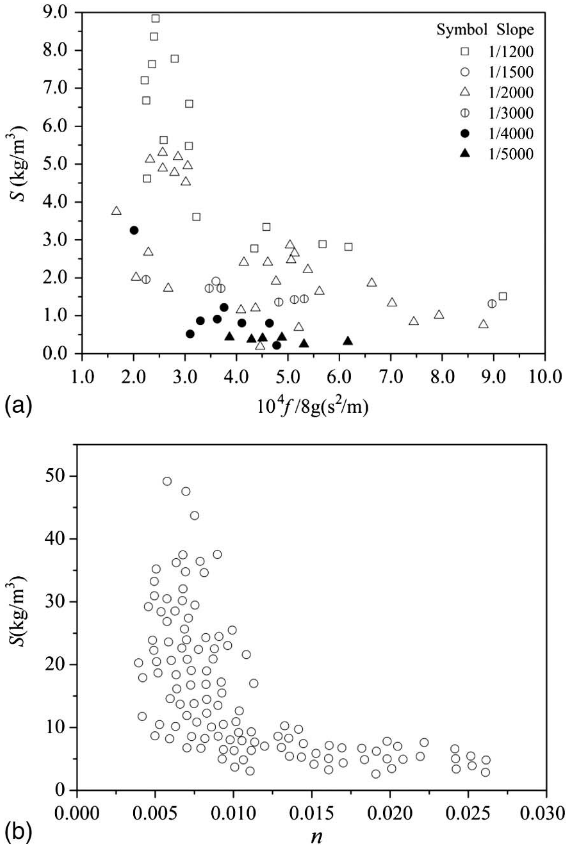

Fig. 2. Observed reduction in resistance coefficients, Darcy-Weisbach f and Manning's n, with sediment concentration S: (a) experimental data from the Nanjing Hydraulic Research Institute (NHRI); and (b) field data from the Yellow River. (Data from Zhang 1961.)

flow. The idea was validated by measurement data from experiments [e.g., Fig. 2(a)] and in many hydrologic stations along the Yellow River [e.g., Fig. 2(b)]. Very low values of the Manning's n (even less than 0.01) occurred with heavy sediment concentrations. Such low values of Manning's n can be attributed to the damping of turbulence intensity due to heavy sediment concentrations.

Considering that the energy loss due to the resistance to the sediment-laden flow (with suspended sediment particles) is less than that to the clear-water flow (without suspended sediment particles) under the same condition, Zhang (1959, 1961) defined the difference ΔE as

$$E - E_s = \Delta E \tag{11}$$

where E and E_s = energy losses per unit length and time in clear-water and sediment-laden flows, respectively, and can be written as

$$E = \rho g A U J \tag{12}$$

$$E_s = \rho g(1 - C_v) A U J_s + \rho_s g C_v A U J_s \tag{13}$$

where A = cross-sectional area of flow; U = depth-averaged flow velocity; C_v = suspended sediment concentration by volume; and J and J_s = energy slopes in clear-water and sediment-laden flows, respectively.

The ΔE is due to the damping of turbulence intensity in the presence of suspended sediment particles. Zhang assumed that ΔE depends on A, C_v, particle settling velocity w_s, and submerged specific weight $\Delta\rho g$. Applying dimensional analysis, the following equation of ΔE can be obtained:

$$\Delta E = \Delta\rho g A w_s f(C_v) \tag{14}$$

Inserting Eqs. (12)–(14) into Eq. (11) and assuming $f(C_v) = \alpha C_v^\eta$ yields

$$\rho g A U J - [\rho g(1 - C_v) A U J_s + \rho_s g C_v A U J_s] = \alpha \Delta\rho g A w_s C_v^\eta \tag{15}$$

Neglecting the smaller order term, $\Delta\rho g C_v A U J_s$, and rearranging, Eq. (15) reduces to

$$C_v^\eta = \frac{1}{\alpha\Delta}(J - J_s)\frac{U}{w_s} \tag{16}$$

The energy slopes for clear-water and sediment-laden flows are given by the Darcy-Weisbach relations:

$$J = \lambda \frac{1}{4R}\frac{U^2}{2g} \tag{17}$$

$$J_s = \lambda_s \frac{1}{4R}\frac{U^2}{2g} \tag{18}$$

where λ and λ_s = friction factors in clear-water and sediment-laden flows, respectively; and R = hydraulic radius. Inserting Eqs. (17) and (18) into Eq. (15) yields

$$C_v^\eta = \frac{1}{8\alpha\Delta}(\lambda - \lambda_s)\frac{U^3}{gRw_s} \tag{19}$$

Replacing $\lambda - \lambda_s = \alpha_1 C_v^\beta$, the suspended sediment concentration C_m ($=\rho_s C_v$) in mass per unit volume is given by

$$C_m = k\left(\frac{U^3}{gRw_s}\right)^m \tag{20}$$

where $k = \rho_s[\alpha_1/(8\alpha\Delta)]^m$; and $m = 1/(\eta - \beta)$.

Eq. (20) is similar to the equation (with $m = 1$) derived by Velikanov (1955, 1958), but based on different concepts. Velikanov (1955, 1958) used the gravitational theory of sediment transport, which divides the rate of energy dissipation in sediment-laden flow into two parts: the power required to overcome the flow resistance and the power required to maintain sediment in suspension. Zhang (1959, 1961) used the hypothesis of the turbulence attenuation by suspended sediment. Including the exponent m allows Eq. (20) to cover a much wider range of applications than the equation of Velikanov.

Zhang (1961) calibrated Eq. (20) using a large number of experimental data obtained by the Wuhan Institute of Hydraulic and Electrical Engineering (WIHEE) and the Nanjing Hydraulic Research Institute (NHRI), and field data from the Yangtze and Yellow Rivers and other sources, as shown in Fig. 3. To represent the C_m and $U^3/(gRw_s)$ curve, the exponent m in Eq. (20) varies between 0.4 and 1.5 and the coefficient k varies over a large range. For convenience, Guo (2002) suggested the following relationship to approximate Eq. (20):

$$C_m = \frac{1}{20}\left(\frac{U^3}{gRw_s}\right)^{1.5}\left[1 + \left(\frac{1}{45}\frac{U^3}{gRw_s}\right)^{1.15}\right]^{-1} \tag{21}$$

As the suspended-load in a river may consist of a wide range of sediment sizes, it is important to determine the representative sediment size for using Eq. (20). It was suggested to use the average diameter or average settling velocity of the suspended sediment

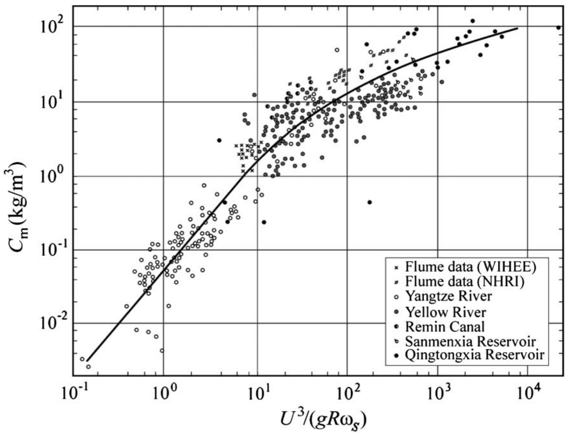

Fig. 3. Relation (solid line) between suspended sediment concentration C_m and $U^3/(gRw_s)$ obtained from the fitting experimental and field data plots. (Data from Zhang 1961.)

mixture. Wu and Li (1992) extended Eq. (20) to multiple-sized suspended sediment, by dividing the sediment mixture into a suitable number of size classes and applying Eq. (20) to each size class. The total transport capacity is calculated as the sum of the fractional values multiplied with the fraction of each size class in bed-material. Wu et al. (2000) tested this approach using a large number of measurement data collected by Toffaleti (1968), including the experimental data observed by three groups of investigators: Nomicos, Einstein-Chien and Vanoni-Brooks, and the field data in the Rio Grande, Middle Loup, Niobrara, and Mississippi Rivers. These data cover flow discharges up to 21,600 m^3/s, flow depths up to 17.5 m, and sediment sizes from 0.062 to 1 mm. The Zhang's (1961) formula, Eq. (20), performs as well as the later developed Karim (1998) and Wu et al. (2000) formulas.

Eq. (20) has been widely used in many engineering analyses and numerical models. Two examples are given here. Eq. (20) was successfully used by Fang and Wang (2000) in a three-dimensional model to simulate the suspended-load deposition in the near-dam reach of the Three Gorges Reservoir. Wu (2013) used Eq. (21) together with the bed-load formula of Wu et al. (2000) in a dam and levee breach model to determine the sediment entrainment by the strong, highly transient dam and levee breach flows. The Zhang's (1961) formula has a unique feature that the slope of the curve in Fig. 3 or the exponent m decreases as $U^3/(gRw_s)$ increases. This can reduce the possibility of unrealistically high sediment transport capacity at high flows (Wu 2013).

Summary

Rui-Jin Zhang was a great scientist and educator. His formulas of sediment settling velocity and transport capacity, with his many other theories and methods, made significant contributions to sediment engineering. He developed these formulas through numerous laboratory and field observations, sound physical insights, simple but thoughtful mathematical formulations, and thorough calibrations using available measurement data. These formulas are still among the best formulas available in literature. The authors of this forum article would like the international sedimentation engineering community to find more use of these formulas and improve them if needed. Some of Zhang's other theories and methods can be found in the English reference books of Zhang and Xie (1993), Chien and Wan (1999), and Wu (2007).

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