Fundamentals of Sediment Transport

Weiming Wu, PhD
Professor
Dept. of Civil and Environmental Eng.
Clarkson University
Potsdam, NY 13699, USA

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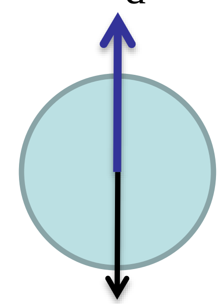
Sediment Settling Velocity

Submerged weight = drag force

$$W_s = (\rho_s - \rho) g a_1 d^3 \qquad F_d = C_d \rho a_2 d^2 \frac{\omega_s^2}{2}$$



One derives

$$\omega_s = \left(\frac{a_1}{a_2} \frac{2}{C_d} \frac{\rho_s - \rho}{\rho} g d \right)^{1/2}$$

where ω_s is the settling velocity, d is the diameter, and C_d is the drag coefficient.

C_d and ω_s have general relations:

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

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

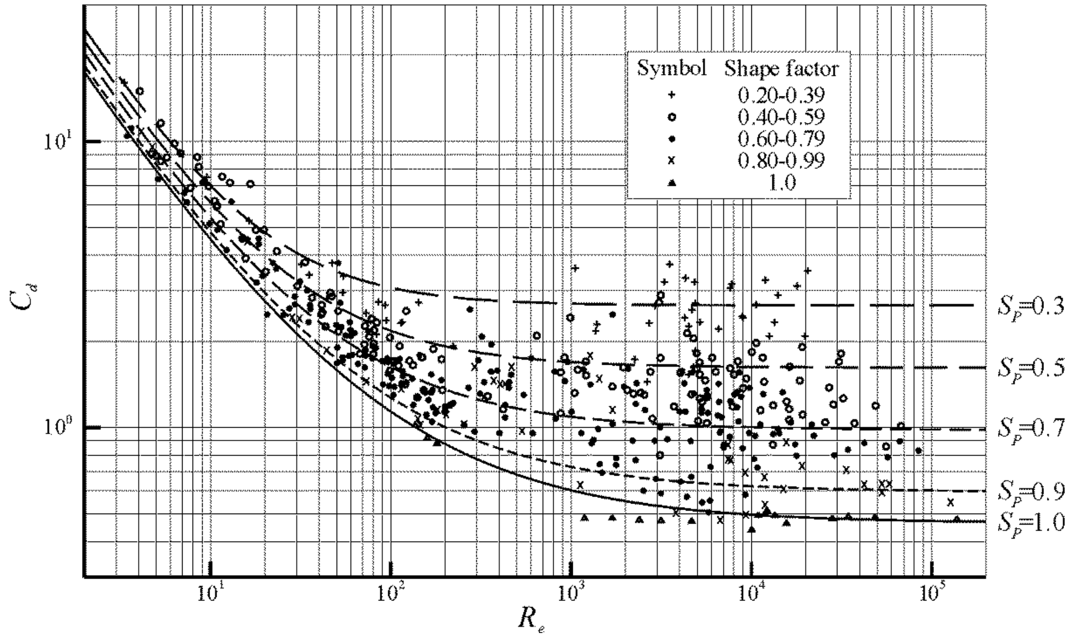
Author	M	N	
Rubey (1933)	24	2.1	1
Zhang (1961)	34	1.2	1
Zanke (1977)	24	1.1	1
Raudkivi (1990)	32	1.2	1
Julien (1995)	24	1.5	1
Cheng (1997)	32	1	1.5

Wu and Wang (2006) plotted C_d ~ Re relation shown in the right figure, and established empirical formulas:

$$M = 53.5e^{-0.65S_P}$$

$$N = 5.65e^{-2.5S_P}$$

$$n = 0.7 + 0.9S_P$$



Wu and Wang (2006) compared more than ten sediment settling velocity formulas, and found that the formulas of Zhang (1961), Hallermeier (1981), Dietrich (1982), Cheng (1997), Ahrens (2000), Jimenez and Madsen (2003), and Wu and Wang (2006) have comparable and reasonable reliabilities for predicting the settling velocity of naturally worn sediment particles (with a Corey shape factor of about 0.7). The average errors normally are less than 9%.

Sediment Deposit Porosity

Han et al. (1981) formula for uniform sediment deposit:

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

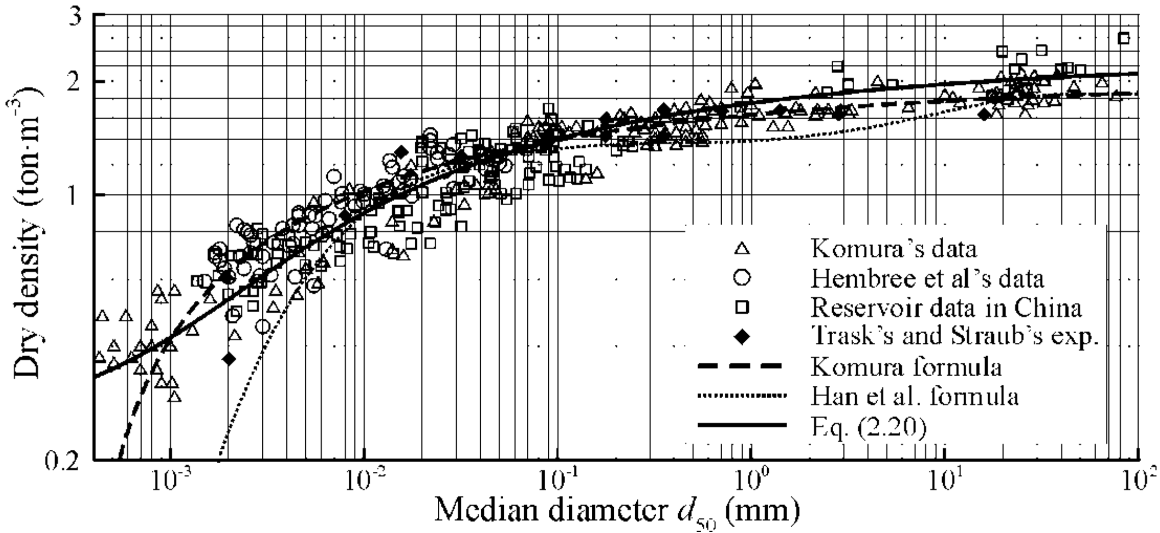
where d is the sediment size in mm; d_0 is a reference size of 1 mm; and δ_1 is the thickness of the water film attaching to sediment particles, given a value of about 0.0004 mm.

For a nonuniform sediment deposit, fine particles may fill the voids among coarse particles. If the filling is negligible, the Colby (1963) method can be used:

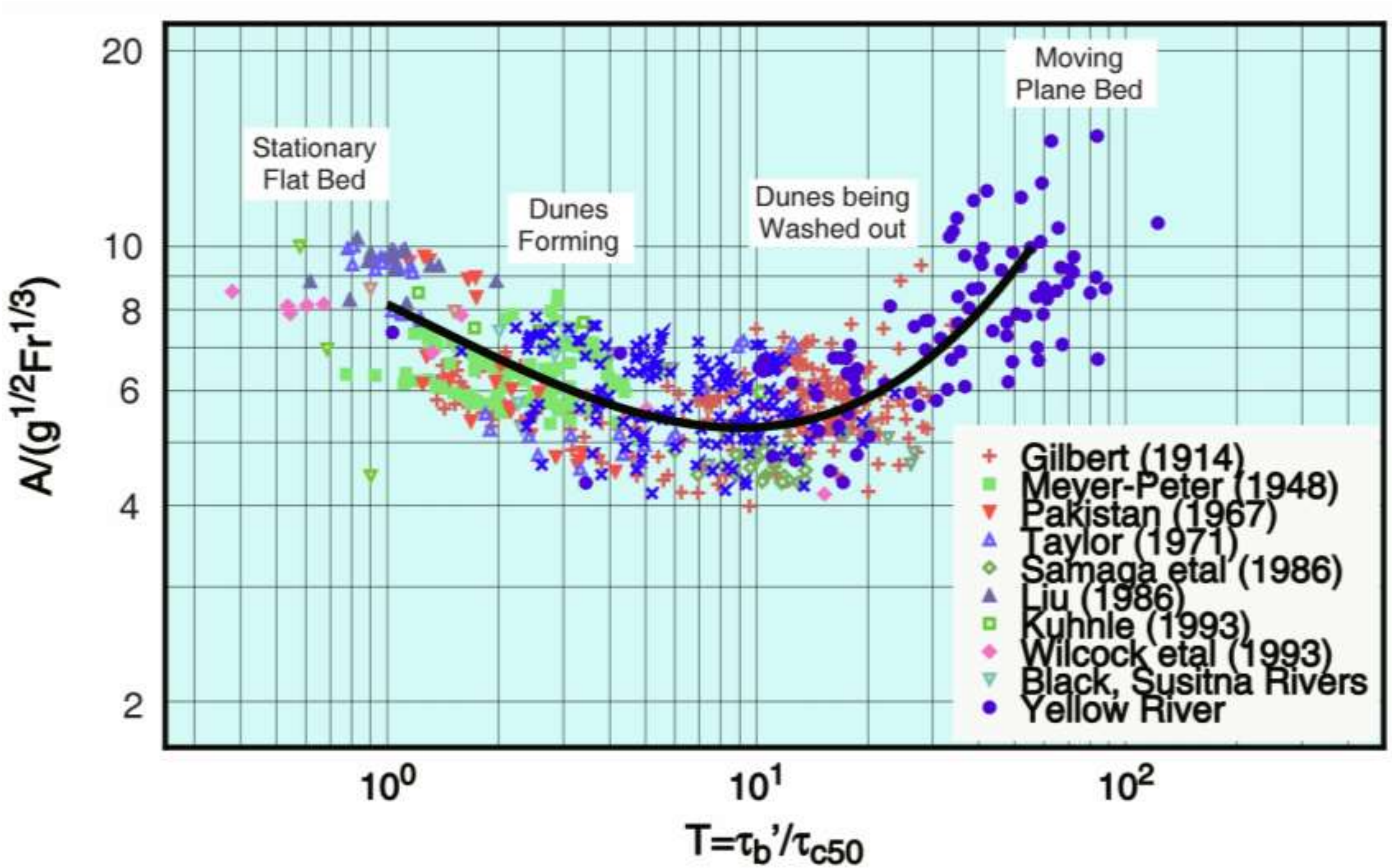
$$\frac{1}{1 - p'_m} = \sum_{k=1}^{N} \frac{p_k}{1 - p'_{mk}}$$

Wu and Wang (2006) modified the Komura (1963) formula as

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



Movable Bed Roughness



Wu and Wang (1999, JHE, No. 12)

Predicted vs. Measured Flow Depths (4,376 data points)

Error Range	% of Calculated Flow Depths in Error Range			
	Li-Liu	van Rijn	Karim	Wu-Wang
±10%	21.8	44.0	41.0	41.5
±20%	41.8	77.9	74.9	75.9
±30%	58.8	91.4	91.0	94.4

Interactions among Nonuniform Sediments on the Bed

- Coarse particles have higher chances of exposure to flow, while fine particles are more likely sheltered by coarse particles.
- It is important to consider the effect of this hiding and exposure mechanism on nonuniform sediment transport.
- The widely used approach is to introduce correction factors into the existing formulas of uniform sediment incipient motion and transport:

$$\eta_k = f(d_k/d_m \quad or \quad d_k/d_{50})$$

where d_k = size of kth sediment fraction, d_m= mean diameter of bed material; d_{50}= median diameter of bed material.

Hiding and Exposure Correction Factor

Clarkson UNIVERSITY defy convention

Egiazaroff (1965) Formula:

$$\frac{\Theta_{ck}}{\Theta_c} = \left[\frac{\log 19}{\log(19 d_k / d_m)}\right]^2$$

with the Shields number $\Theta_{ck} = \tau_{ck} / [(\gamma_s - \gamma) d_k]$

Ashida and Michiue (1971) Formula:

$$\frac{\Theta_{ck}}{\Theta_c} = \begin{cases} [\log 19 / \log(19 d_k / d_m)]^2 & d_k / d_m \geq 0.4 \\ d_m / d_k & d_k / d_m < 0.4 \end{cases}$$

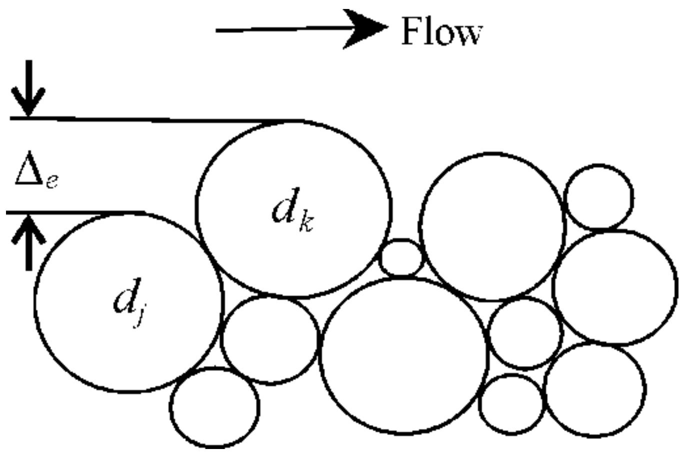
Paker et al. (1982) Formula:

$$\Theta_{ck} = \Theta_{c50} \left(\frac{d_k}{d_{50}}\right)^{-m}$$

m is an empirical coefficient between 0.5–1.0

Hiding and Exposure (Wu et al., 2000)

Exposure height of a particle on the bed, Δ_e, is defined as the difference between the apex elevations of it and the upstream particle.



If $\Delta_e>0$, the particle is at an exposed state; if $\Delta_e<0$, it is at a hidden state. For a particle with diameter d_k in the bed surface layer, the value of Δ_e is in the range between d_k and $-d_j$. Here, d_j is the diameter of the upstream particle. Δ_e is assumed to have a uniform probability distribution function:

$$f = \begin{cases} 1/(d_k + d_j), & -d_j \le \Delta_e \le d_k \\ 0, & \text{otherwise} \end{cases}$$

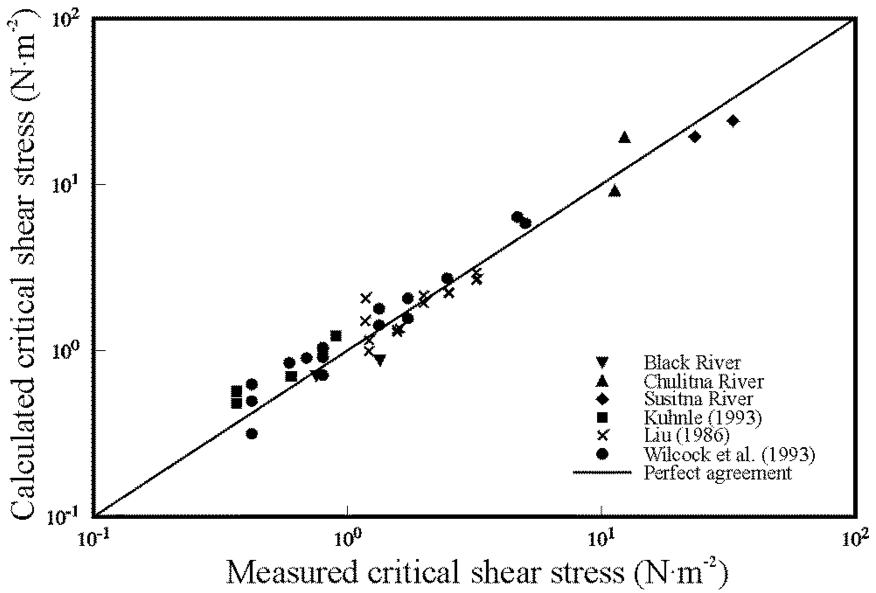
The hidden and exposed probabilities of particles d_i on the bed are:

$$p_{hk} = \sum_{j=1}^{N} p_{bj} \frac{d_j}{d_k + d_j} \qquad p_{ek} = \sum_{j=1}^{N} p_{bj} \frac{d_k}{d_k + d_j}$$

The criterion for sediment incipient motion proposed by Shields (1936) is then modified as

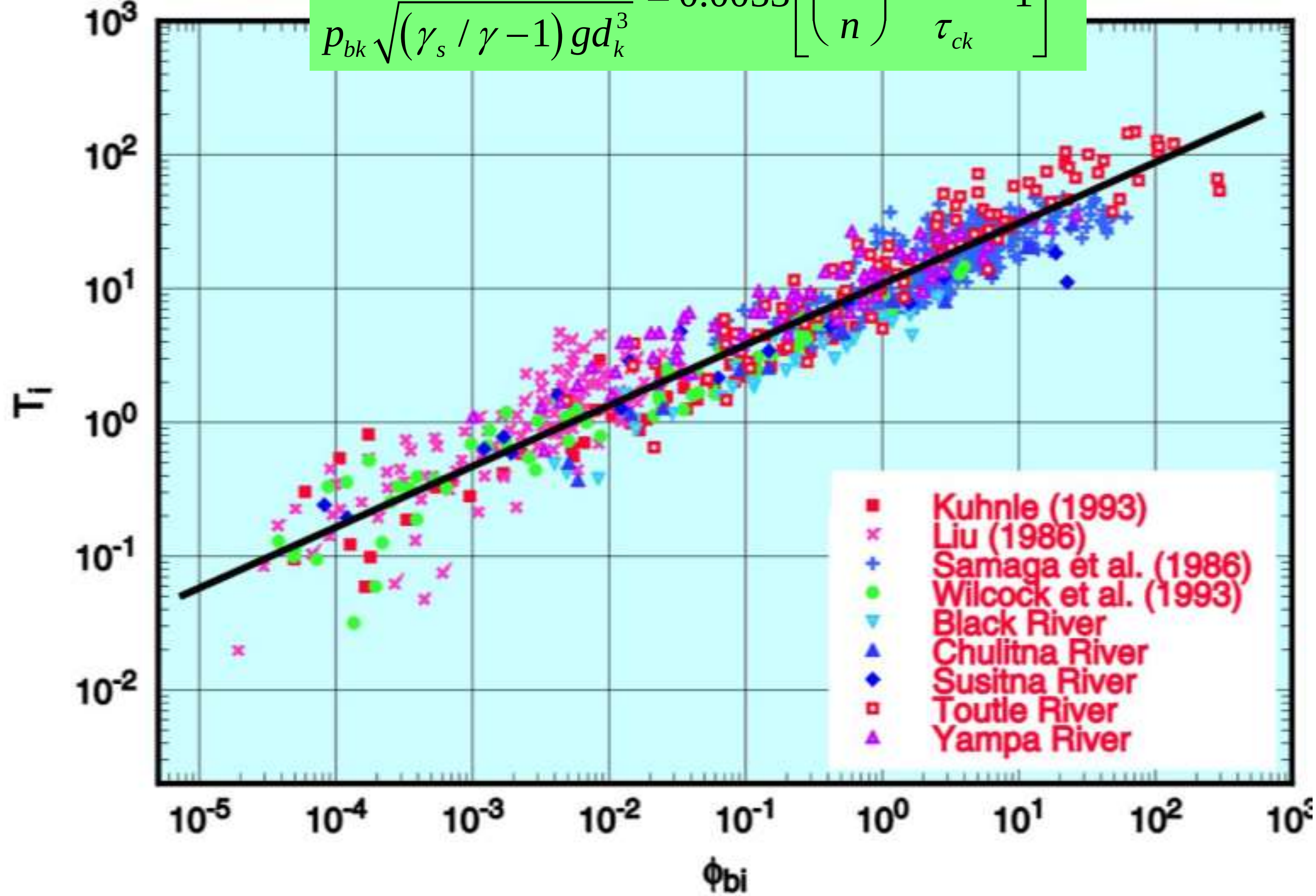
$$\frac{\tau_{ck}}{(\gamma_s - \gamma) d_k} = \Theta_c \left(\frac{p_{ek}}{p_{hk}} \right)^{-m}$$

where Θ_c=0.03, and m=0.6, as calibrated.



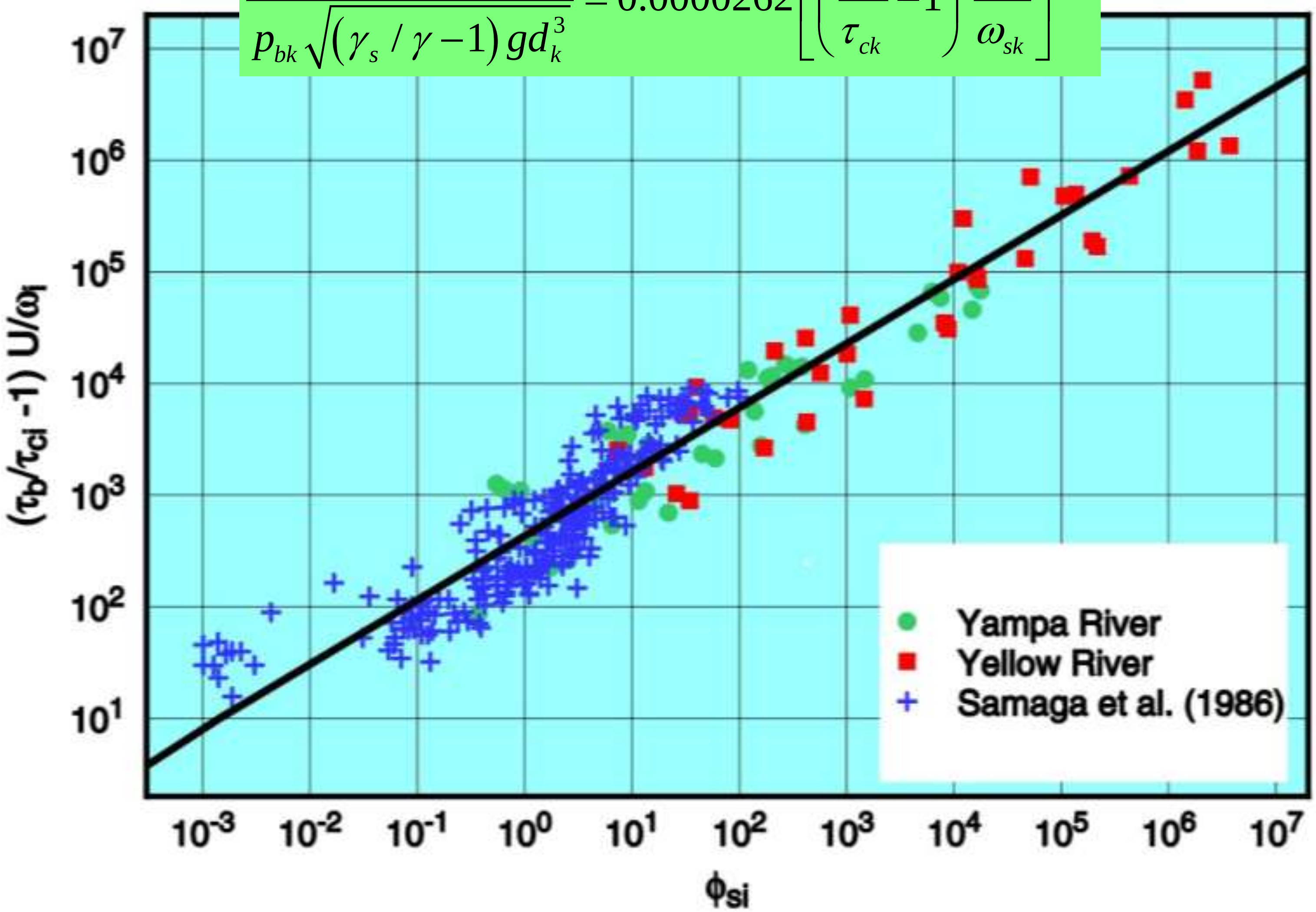
Wu et al. (2000) Bed Load Formula

$$\frac{q_{bk}}{p_{bk}\sqrt{\left(\gamma_s/\gamma-1\right)gd_k^3}}=0.0053\left[\left(\frac{n'}{n}\right)^{3/2}\frac{\tau_b}{\tau_{ck}}-1\right]^{2.2}$$



Wu et al. (2000) Suspended Load Formula

$$\frac{q_{sk}}{p_{bk}\sqrt{(\gamma_s/\gamma-1)gd_k^3}} = 0.0000262\left[\left(\frac{\tau}{\tau_{ck}}-1\right)\frac{U}{\omega_{sk}}\right]^{1.74}$$



Comparison of Sediment Transport Capacity Formulas Using Brownlie's (1981) Data of Uniform Bed Load

Error Ranges	Percentages (%) of Calculated Transport Rates in Error Ranges				
	Van Rijn	Engelund & Fredse	Bagnold	Meyer-Peter & Mueler	Wu et al.
0.8≤r≤1.25	14.8	21.4	21.4	21.3	38.7
0.67≤r≤1.5	25.3	37.4	38.9	39.4	59.3
0.5≤r≤2	44.0	54.1	57.2	66.2	80.1

Note: r = calculation / measurement.

Comparison of Sediment Transport Capacity Formulas Using Brownlie's (1981) Data of Uniform Bed-Material Load

Error Ranges	Percentages (%) of Calculated Transport Rates in Error Ranges				
	Ackers & White	Yang	Engelund & Hansen	SEDTRA	Wu et al.
0.8≤r≤1.25	37.3	33.4	33.6	36.6	40.4
0.67≤r≤1.5	57.9	56.6	55.4	59.1	62.7
0.5≤r≤2	82.4	76.6	77.0	78.1	81.3

Note: r = calculation / measurement.

Comparison of Sediment Transport Capacity Formulas Using Toffaleti's (1968) Data of Nonuniform Bed-Material Load

Error Ranges	Percentages (%) of Calculated Transport Rates in Error Ranges					
	Modified Ackers & W.	Modified Engelund &H.	Karim	Modified Zhang	SEDTRA	Wu et al
$0.5 \le r \le 2$	5.6	27.8	42.7	48.1	56.9	57.9
$0.33 \le r \le 3$	11.1	40.3	63.5	67.9	73.1	76.1
$0.25 \le r \le 4$	20.8	49.0	73.3	80.7	80.9	85.2

Note: r = calculation / measurement.

Verification Scores of Nonuniform Bed-Load Formulas (Ribberink et al., 2002)

Formula	Transport Rate	Mean Diameter	Average
Wu et al.	0.43	0.86	0.64
E&H	0.34	0.63	0.49
A&W + Day	0.37	0.59	0.48
Parker (surface)	0.23	0.73	0.48
A&W + P&S	0.34	0.49	0.42
van Rijn	0.18	0.54	0.36
MP&M + Egiaz.	0.26	0.34	0.30
MP&M + A&M	0.29	0.29	0.29
MP&M + Hunziker	0.19	0.30	0.25

(Factor n over/underestimation gives a score of 1/n)

Reliable Transport Capacity Formulas

Single-sized total load

Ackers-White (1973) formula is good for coarse sediment, not for fine sediment
Laursen (1958) formula is good for fine sand and silt, not for coarser sediment
Yang's (1973, 1984) formula has two sets of coefficients for sand and gravel
Wu et al. (2000) and Engelund-Hansen (1967) are good for wider size ranges

Sing-sized bed load

Wu et al. (2000) formula
Meyer-Peter and Mueller (1948) formula

Single-sized suspended load

Zhang (1961) formula

Multiple-sized total load

Wu et al. (2000) formula is the top choice

*: Ultimately, calibration using measurements is the most reliable approach.

Nonuniform Sediment Transport under Currents and Waves

(Wu and Lin, 2014)

Nonuniform Sediments in Rivers

View of the Ooi River, Japan, showing sorting of gravel and sand on bars. From Ikeda (2001)

Bed armoring, River Wharfe, UK. From Powell (1998)

Nonuniform Sediments on Coastlines

Gravel-sand beach at Kachemak Bay, Alaska, USA at low tide showing uniformly mixed sand and gravel on the backshore and large cobbles with surficial mud in the lower foreshore. Photograph taken by Peter Ruggiero.

Photograph of a mixed gravel-sand beach at La Jolla, California, USA. Here, gravel and sand material are sorted zonally, with sand at the foreshore and gravel/cobble material along the backshore. Cobbles result from cliff erosion at the back of the beach. Photograph taken by K. Todd Holland.

Sediments near Mississippi River Estuary

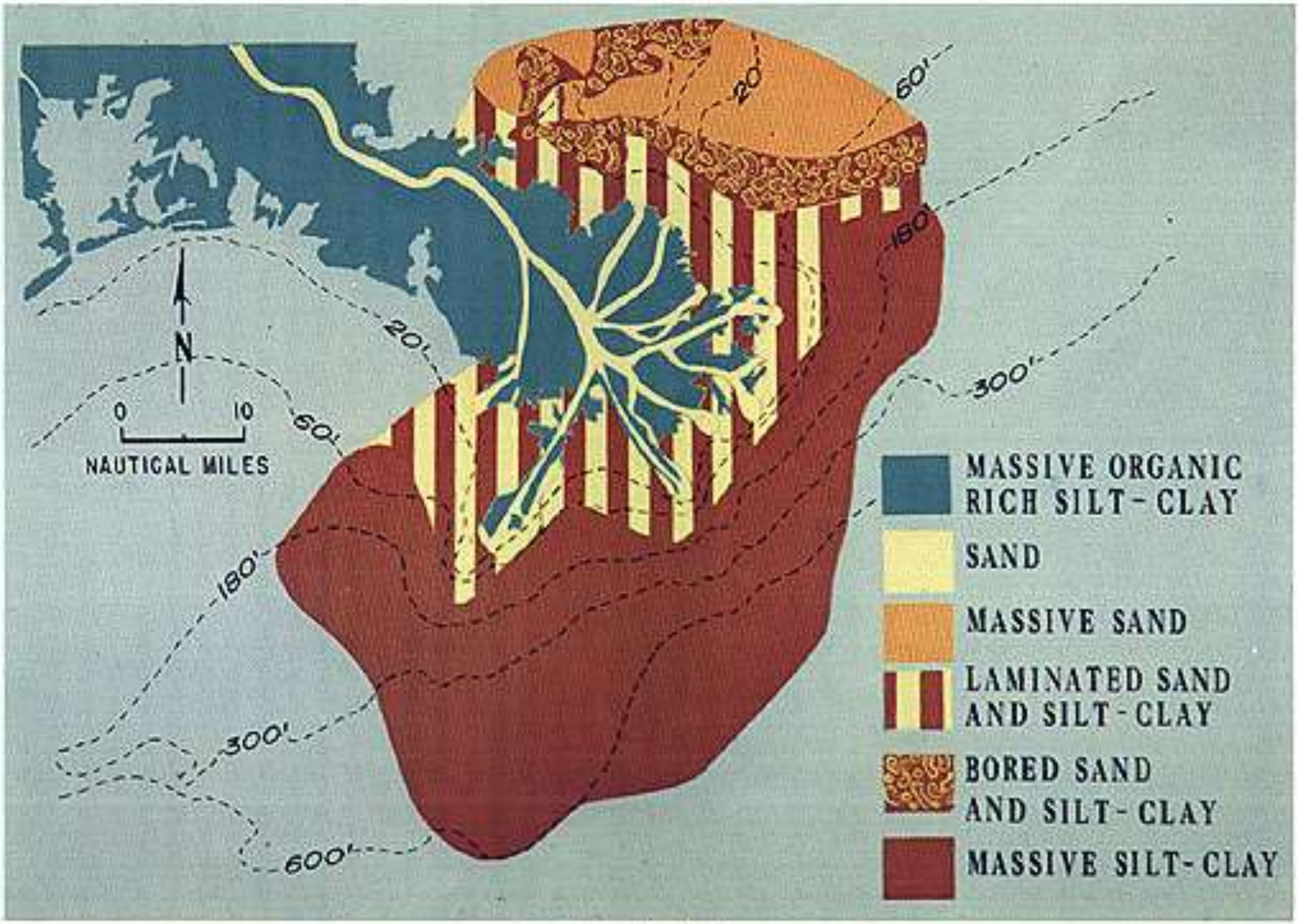
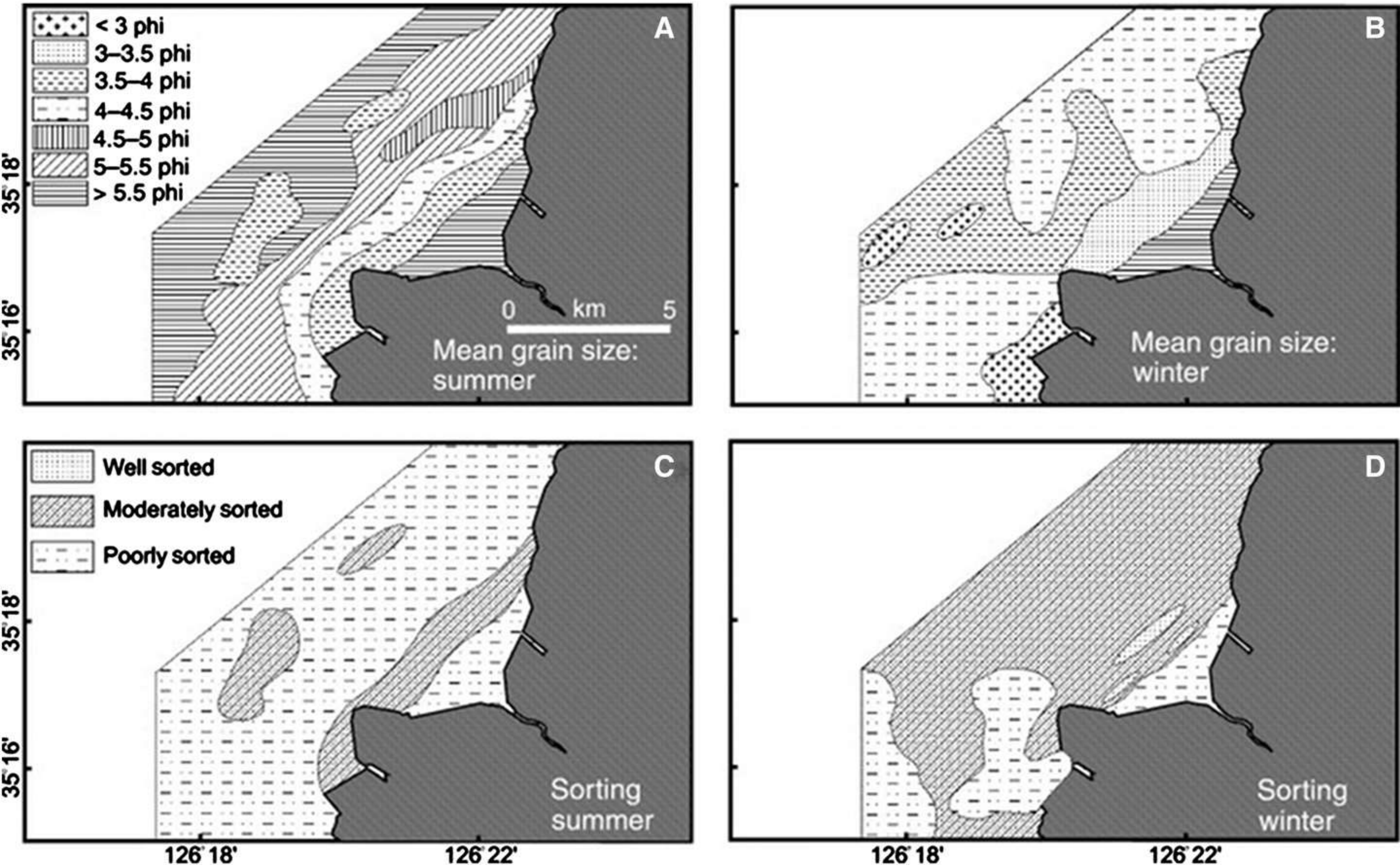


Fig. 26 – Distribution of Mississippi deltaic deposits characterized by sedimentary features. Data northeast of delta. (After Moore and Scruton, 1957.)

Sediment Size and Sorting on Baeksu Tidal Flat, Korea



Mean grain size (A, B) and sorting (C, D) data published in Yang et al. (2005) for sediments of the Baeksu tidal flat, South Korea. Maps derived from grab samples. Data for (A) and (C) are for summer 1998 and (B) and (D) for winter 1999. These data indicate temporal dependence on heterogeneity as sediments become coarser and more poorly sorted in the winter due to increased incident wave energy. A cross-shore gradient in mean grain size N1ϕ persists during both seasons. (Holland and Elmore, 2008)

Bed Shear Stress due to Current

Bed shear stress (grain + form):

$$\tau_{b,c} = \frac{\rho g n^2}{h^{1/3}} U_c^2$$

where U_c is current velocity, h is flow depth, n is the Manning roughness coefficient. n can be specified using reference values or determined by

$$n = h^{1/6} \Big/ \left[18 \log(12h / k_s)\right]$$ with $$k_s = k_s' + k_s''$$

Grain roughness $k_s' = 3d_{90}$ Single-sized $1.5d_{90}$ Multiple-sized

Form roughness $k_s'' = A_r \Delta_r^2 / \lambda_r$

$$\Delta_r = 0.074 \lambda_r d_{mm}^{-0.253} \qquad \lambda_r = 245 d_{mm}^{0.35}$$

Raudkivi (1998)

Bed shear stress due to grain roughness

$$\tau_{b,c}' = \frac{1}{2} \rho f_c' U_c^2$$ with $$f_c' = 2\left(\frac{n'}{n}\right)^{1.5} \frac{g n^2}{h^{1/3}}$$

Bed Shear Stress due to Waves

Total and grain bed shear stresses (Josson, 1966)

$$\tau_{b,wm} = \frac{1}{4}\rho f_w U_w^2 \qquad \tau'_{b,wm} = \frac{1}{4}\rho f_w' U_w^2$$

with Soulsby (1997) formula

$$f_w = 0.237\left(A_w / k_s\right)^{-0.52} \qquad f_w' = 0.237\left(A_w / k_s'\right)^{-0.52}$$

Total roughness

$$k_s = k_s' + k_s''$$

Form roughness (Soulsby and Whitehouse, 2005)

$$\lambda_r = \frac{A_w}{1.0 + 0.00187\frac{A_w}{d_{50}}\left\{1.0 - \exp\left[-\left(0.0002\frac{A_w}{d_{50}}\right)^{1.5}\right]\right\}}$$

$$\Delta_r = 0.15\lambda_r\left\{1.0 - \exp\left[-\left(5000\frac{d_{50}}{A_w}\right)^{3.5}\right]\right\}$$

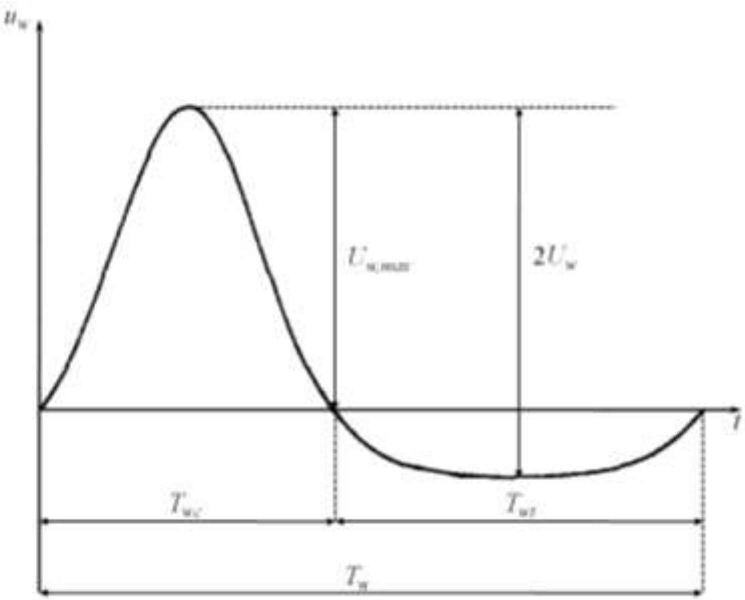
$$A_w = U_w T_w / 2\pi$$

Asymmetric Waves

Second-order Stokes waves

$$u_w(t) = U_w\left(\cos\omega t + r_w \cos 2\omega t\right)$$

with $r_w = u_{w,max}/U_w - 1$



Bed shear stress due to grain roughness (Camenen, 2002)

$$\tau'_{b,wm.on} = \frac{1}{2}\rho f'_w \frac{U_w^2}{2}\left(1 + r_w^2 + \frac{13}{6} r_w \frac{\sin a_c}{a_c} + \frac{1}{6}\frac{\sin 2a_c}{2a_c}\right)$$

$$\tau'_{b,wm.off} = \frac{1}{2}\rho f'_w \frac{U_w^2}{2}\left(-1 - r_w^2 + \frac{13}{6} r_w \frac{\sin a_t}{a_t} - \frac{1}{6}\frac{\sin 2a_t}{2a_t}\right)$$

Bed Shear Stress due to Currents and Waves

Grain shear stress

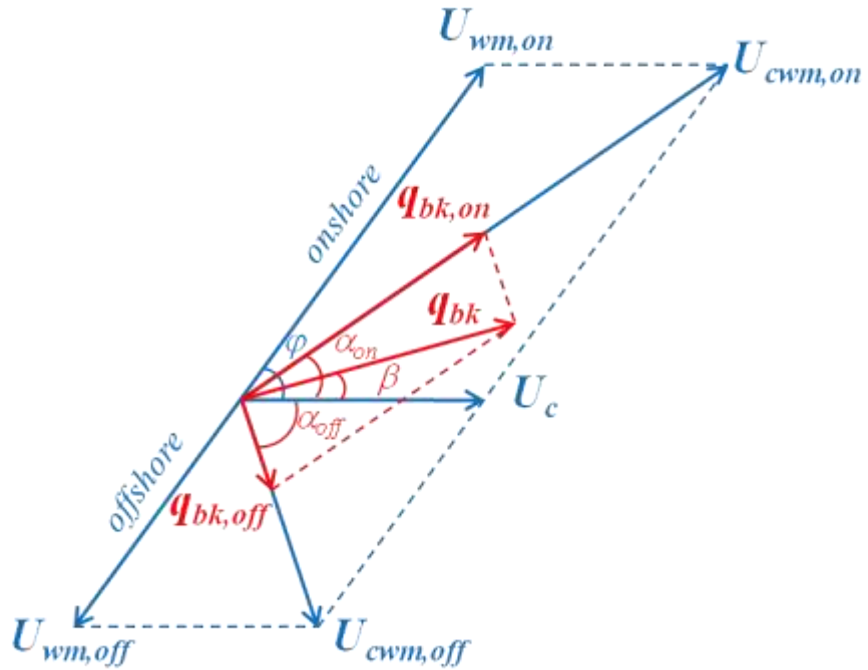
$$\tau'_{b,on} = \frac{1}{2}\rho f'_{cw}\left(U_c^2 + U_{wm,on}^2 + 2U_c U_{wm,on}\cos\varphi\right)$$

$$\tau'_{b,off} = \frac{1}{2}\rho f'_{cw}\left(U_c^2 + U_{wm,off}^2 + 2U_c U_{wm,off}\cos(\pi-\varphi)\right)$$

with

$$f'_{cw} = X_u f'_c + (1 - X_u) f'_w$$

$$X_u = U_c^2 \Big/ \left(U_c^2 + 0.5U_w^2\right)$$



Nonuniform Bed Load

Bed-load transport rates in onshore and offshore half cycles

$$q_{bk,on} = 0.0053 p_{bk} \sqrt{(\gamma_s / \gamma - 1) g d_k^3} \left(\frac{\tau'_{b,on}}{\tau_{ck}} - 1 \right)^{2.2}$$

$$q_{bk,off} = 0.0053 p_{bk} \sqrt{(\gamma_s / \gamma - 1) g d_k^3} \left(\frac{\tau'_{b,off}}{\tau_{ck}} - 1 \right)^{2.2}$$

Resultant fractional bed-load rate

$$\vec{q}_{bk} = \frac{T_{wc}}{T_w} \vec{q}_{bk,on} + \frac{T_{wt}}{T_w} \vec{q}_{bk,off}$$

where T_{wc} = onshore half cycle
T_{wt} = offshore half cycle
T_w = wave period

Nonuniform Suspended Load

Fractional suspended-load transport rate

$$q_{sk} = 0.0000262\, p_{bk} \sqrt{(\gamma_s / \gamma - 1) g d_k^3} \left[\left(\frac{\tau_b}{\tau_{cri,k}} - 1 \right) \frac{U_c}{\omega_{sk}} \right]^{1.74}$$

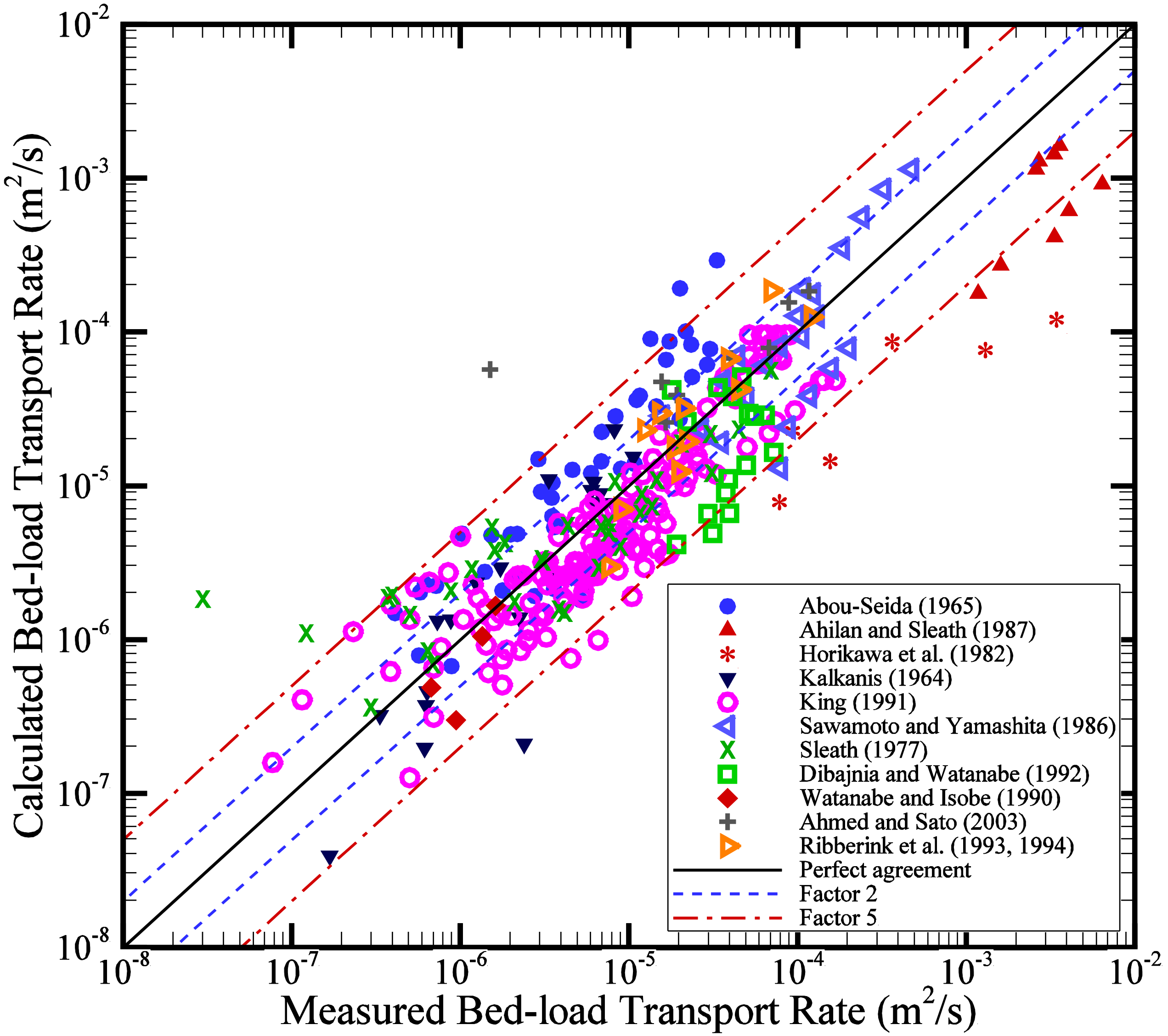
where U_c = current velocity; and bed shear stress

$$\tau_b = \sqrt{\tau_{b,c}^2 + \tau_{b,wm}^2 + 2\tau_{b,c}\tau_{b,wm}\cos\varphi}$$

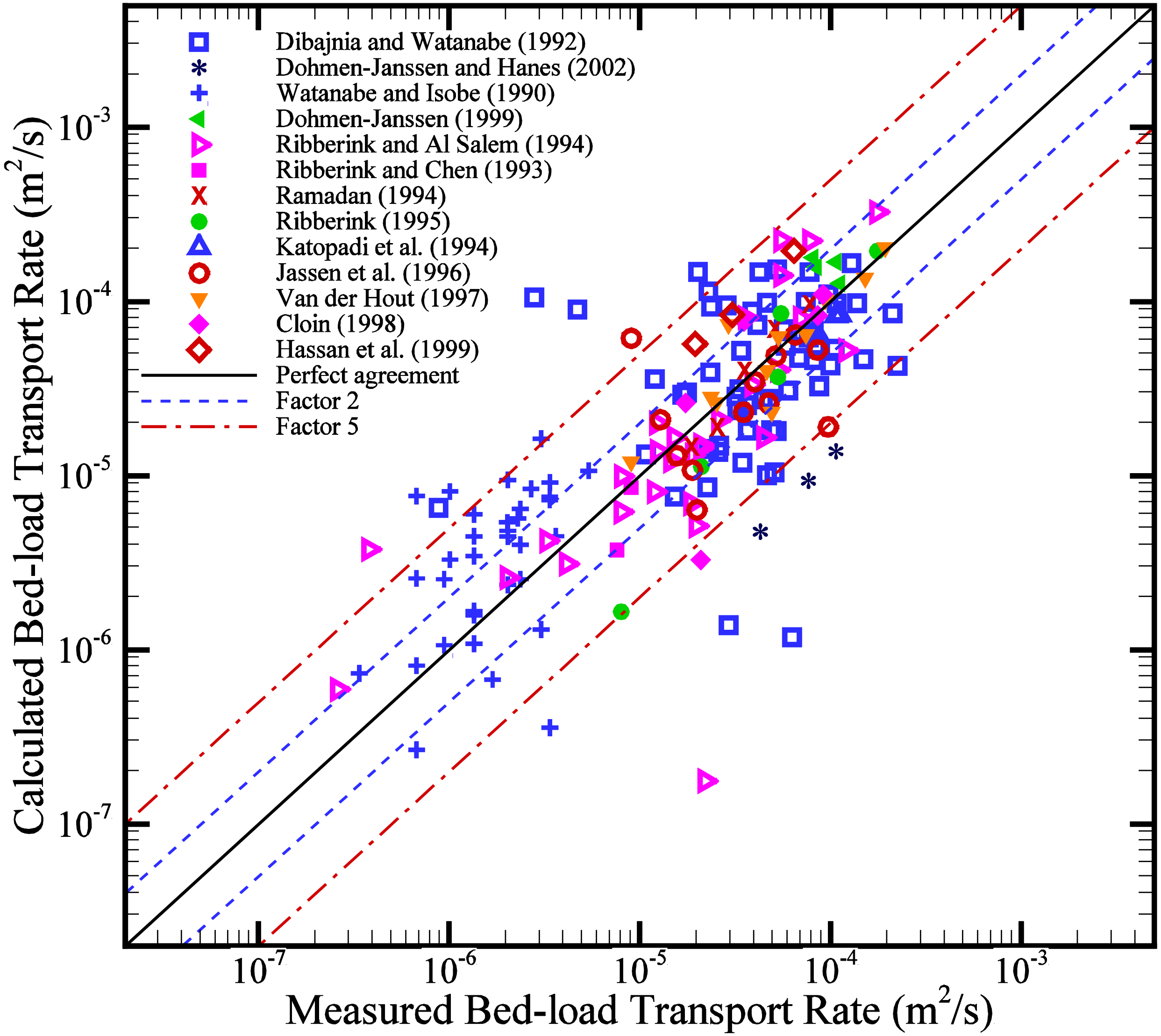
Summary of Uniform Bed-Load Data under Current and Waves (Camenen and Larson, 2007)

Author(s)	Exp. facility	Cycle	No. of runs	s	d_{50} (mm)	U_c (m/s)	U_w (m/s)	T_w (s)
Abou-Seida (1965)	OT	Half	9 37	2.23 2.65	0.70 0.14-2.61	0 0	0.41-0.80 0.35-1.28	2.0-4.8 1.7-5.1
Ahilan and Sleath (1987)	OWT	Half	5 4	1.14 1.44	4.0 4.3	0 0	0.32-0.51 1.10-1.22	3.6-3.7 4.7-4.9
Horikawa et al. (1982)	OWT	Half	6	2.66	0.20-0.70	0	0.76-1.27	2.6-6.0
Kalkanis (1964)	OT	Half	27	2.63	1.68-2.82	0	0.28-0.71	3.2-6.2
King (1991)	OWT	Half	178	2.65	0.14-1.10	0	0.30-1.21	2.0-12.0
Sawamoto and Yamashita (1986)	OWT	Half	7 15	1.58 2.65	1.50 0.2-1.8	0 0	0.44-1.25 0.74-1.25	3.8 3.8
Sleath (1977)	OT	Half	12 8 14	1.14 2.58 2.61	3.04 1.89 4.24	0 0 0	0.08-0.17 0.31-0.37 0.27-0.67	1.3-9.0 0.6-2.0 0.5-2.7
Dibajnia and Watanabe (1992)	OWT	Full	25 76	2.65 2.65	0.20 0.20	0 -0.26-0.22	0.63-1.00 0.64-1.00	1.0-4.0 1.0-4.0
Watanabe and Isobe (1990)	OWT	Full	12 51	2.65 2.65	0.18, 0.87 0.18, 0.87	0 -0.30-0.25	0.27-0.43 0.27-0.43	3.0, 6.0 3.0, 6.0
Ahmed and Sato (2003)	OWT	Full	15	2.65	0.21-0.74	0	0.97-1.54	3.0
Ribberink and Chen (1993)	OWT	Full	4 4	2.65 2.65	0.13 0.13	0 0.02-0.06	0.64-1.23 0.64-1.23	6.5 6.5
Ribberink and Al Salem (1994)	OWT	Full	10 30	2.65 2.65	0.21 0.21	0 -0.11-0.56	0.95-1.87 0.37-1.37	5.0-12.0 5.0-12.0
Dohmen-Janssen and Hanes (2002)	LWF	Full	4	2.65	0.24	-0.05 ~ -0.03	0.89-1.05	6.5, 9.1
Dohmen-Janssen (1999)	OWT	Full	27	2.65	0.13-0.32	0.23-0.45	0.46-1.70	4.0-12.0
Ramadan (1994)	OWT	Full	5	2.65	0.21	0.02-0.47	0.81-0.84	6.5
Ribberink (1995)	OWT	Full	5	2.65	0.21	-0.45-0.45	0.86-1.27	6.5
Katopadi et al. (1994)	OWT	Full	4	2.65	0.21	0.18-0.43	0.95-1.69	7.2
Jassen et al. (1996)	OWT	Full	12	2.65	0.13	0.23-0.43	0.49-1.47	4.0-12.0
Van der Hout (1997)	OWT	Full	11	2.65	0.21, 0.32	0.23-0.45	0.46-1.70	4.0-12.0
Cloin (1998)	OWT	Full	5	2.65	0.19	0.01-0.41	0.83-1.49	6.4-7.2
Hassan et al. (1999)	OWT	Full	3	2.65	0.24	0.03	0.83-1.22	6.5

Uniform Bed-Load under Waves only



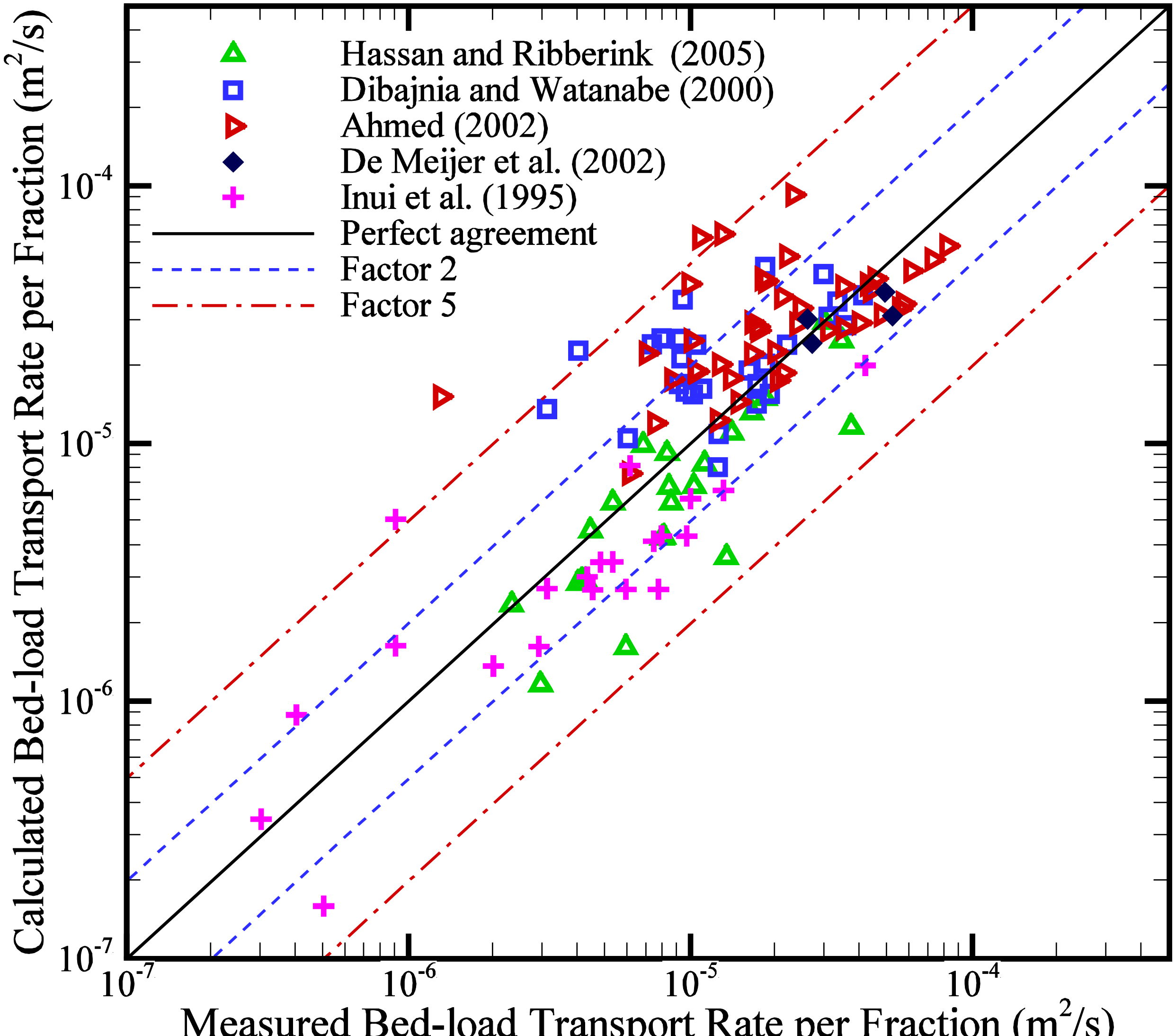
Uniform Bed-Load under Combined Currents and Waves



Summary of Nonuniform Bed-Load Data under Current and Waves

Author(s)	Exp. Facil.	Cycle	No. of runs	No. of sizes	s	d_{50} (mm)	U_c (m/s)	U_w (m/s)	T_w (s)
Ahmed (2002)	OWT	Full	4 15	2 3	2.65 2.51-2.59	0.37-0.47 0.23-0.59	0 0	1.32-1.67 1.17-1.50	3.0 3.0
Hassan and Ribberink (2005)	OWT	Full	5 5	2 3	2.65 2.65	0.15, 0.19 0.24	0 0	0.82-1.20 0.64-1.27	6.5 12.0
O'Dononghue and Wright (2004)	OFT	Full	2 4	2 3	2.65 2.65	0.28 0.19, 0.28	0 0	1.20 1.20	5.0, 7.5 5.0, 7.5
De Meijer et al. (2002)	OWT	Full	1 1	3 3	2.65 2.65	0.19 0.19	0.192 0.371	1.45 0.95	7.20 7.20
Inui et al. (1995)	OFT	Full	16	2	2.65	0.37-0.70	0	0.24-0.77	3.0, 5.0
Dibajnia and Watanabe (2000)	OFT	Full	18	2	2.65	0.29-0.51	0	0.97-1.54	3.0

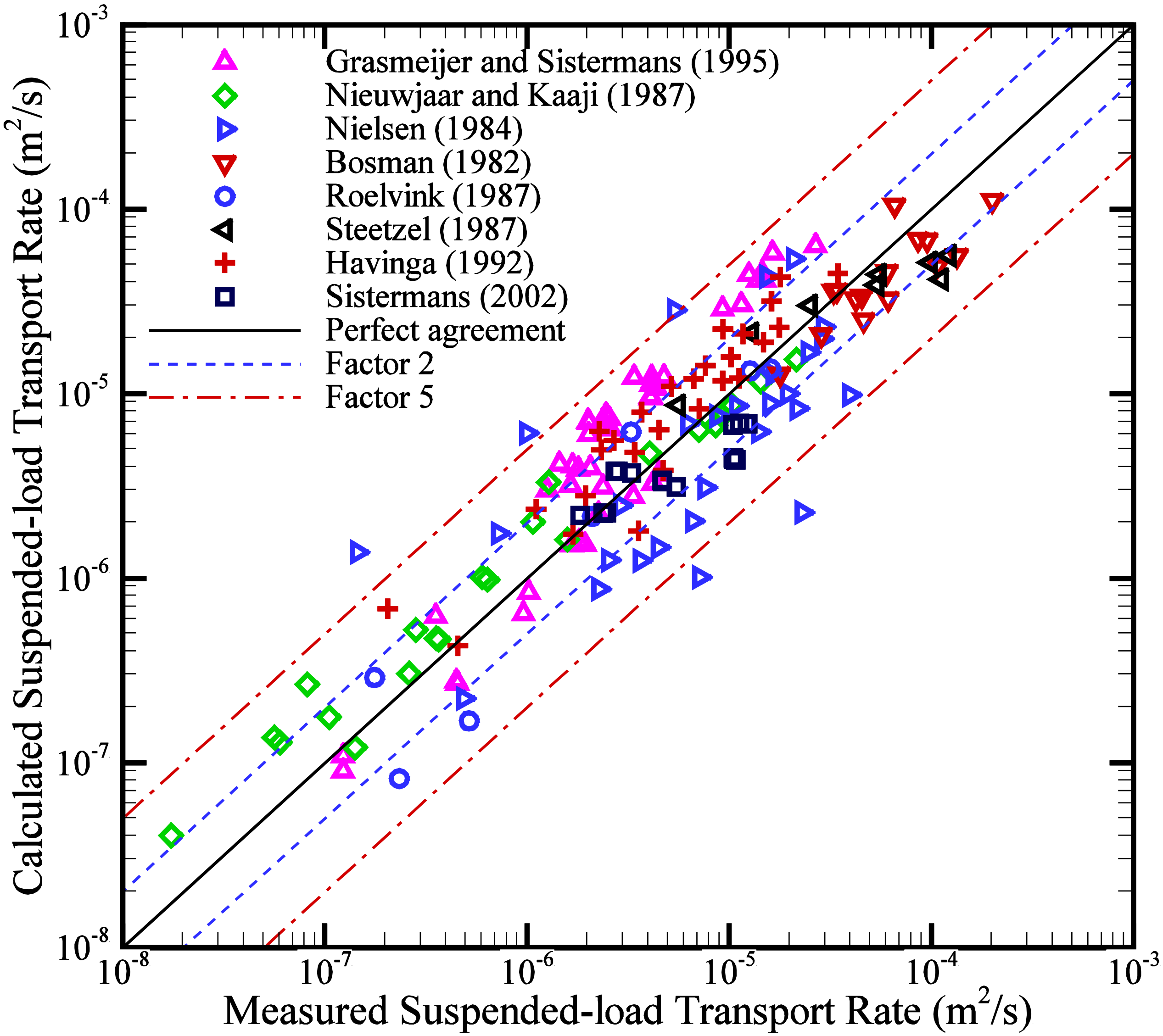
Fractional Bed-Load under Current and Waves



Summary of Uniform Suspended-Load Data under Current and Waves (Camenen and Larson, 2007)

Author(s)	Location	Exp. facility	No. of runs	d_{50} (mm)	h (m)	U_c (m/s)	H_{sig} (m)	T_w (s)
Nielsen (1984)	Australian beaches, Australia	Field	27	0.16-0.49	0.80-1.58	0.04-0.54	0.42-0.80	5.3-12.9
Bosman (1982)	DHL, The Netherlands	Wave flume	16	0.10	0.34-0.56	-0.34-0.32	0.18-0.28	1.7-2.0
Roelvink (1987)	Delft Hydraulic, The Netherlands	Large Scale Flume	11	0.22-0.24	0.71-2.72	-0.11-0.01	0.47-0.73	5.12
Steetzel (1987)	Delft Hydraulic, The Netherlands	Large Scale Flume	8	0.21	0.78-1.63	-0.18~-0.07	0.65-1.10	5.4
Nieuwjaar (1987)	Delft University, The Netherlands	Flume	22	0.20-0.22	0.49-0.52	-0.45-0.45	0.07-0.19	2.4-2.6
Havinga (1992)	Vinje Basin, Delft, The Netherlands	Basin	27	0.10	0.40-0.43	0.10-0.32	0.07-0.14	2.1-2.3
Grasmeijer (1995)	DUT, The Netherlands	Flume	46	0.10	0.29-0.32	-0.04-0.25	0.10-0.17	2.3
Sistermans (2002)	DUT, The Netherlands	Flume	15	0.16-0.19	0.50-0.53	0.20-0.36	0.12-0.19	2.5-2.8

Uniform Suspended-Load under Currents and Waves

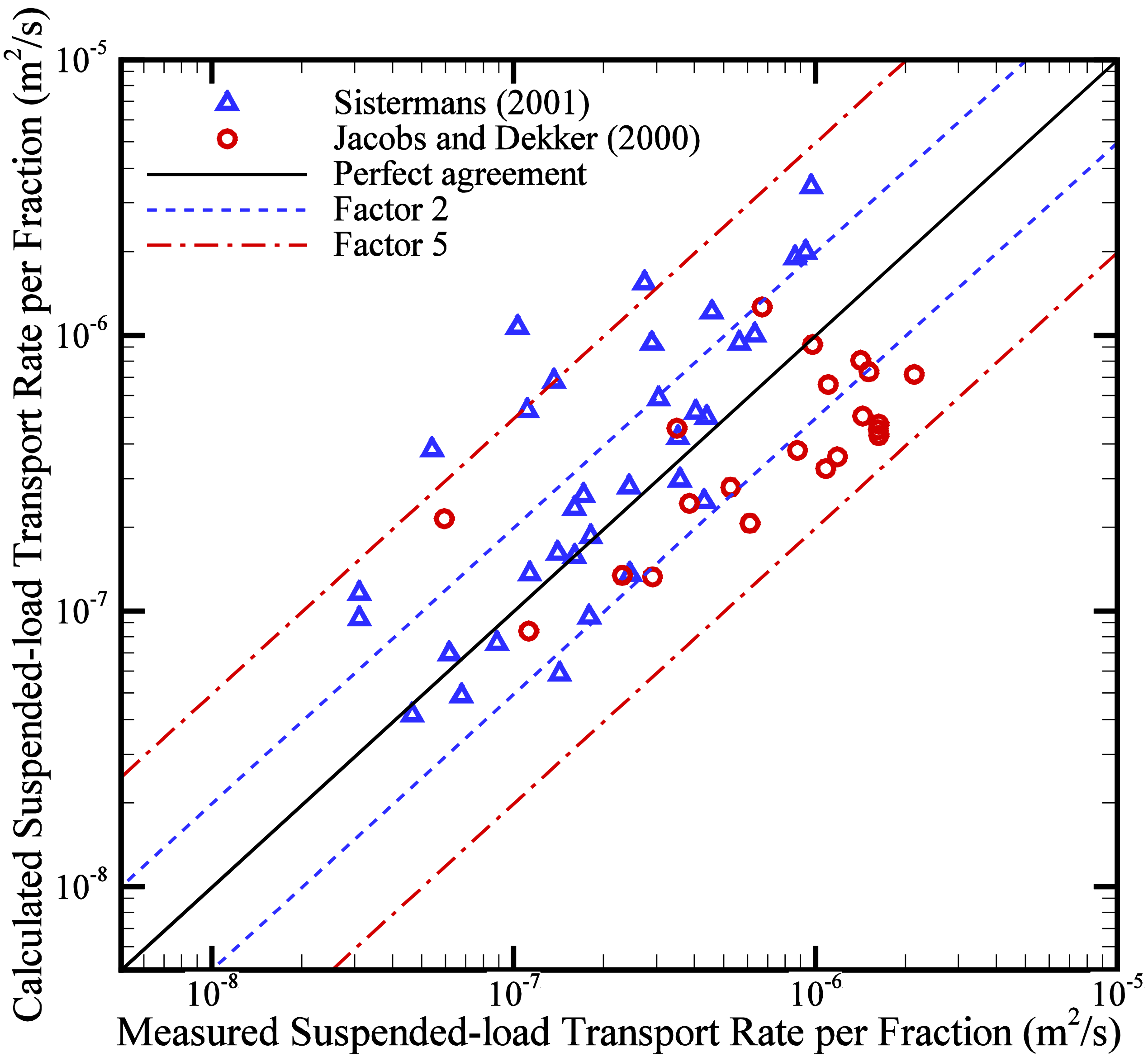


Summary of Nonuniform Suspended-Load Data under Current and Waves

Author(s)	Location	Exp. facility	No. of runs	No. of sizes	d_{50} (mm)	h (m)	U_c (m/s)	H_{sig} (m)	T_w (s)
Jacobs and Dekker (2000)	DUT, The Netherlands	Flume	3	7	0.23 0.26 0.26	0.52 0.49 0.52	0.18 0.19 0.16	0.13 0.15 0.20	2.7 2.8 2.9
Sistermans (2001)	DUT, The Netherlands	Flume	3	13	0.18 0.22 0.21	0.52 0.53 0.52	0.22	0.15 0.19 0.12	2.6 2.7 2.5

Fractional Suspended-Load under Current and Waves

Clarkson UNIVERSITY defy convention



Near-Bed Suspended-load Concentration

Near-bed suspended-load concentration is related to bed-load transport rate:

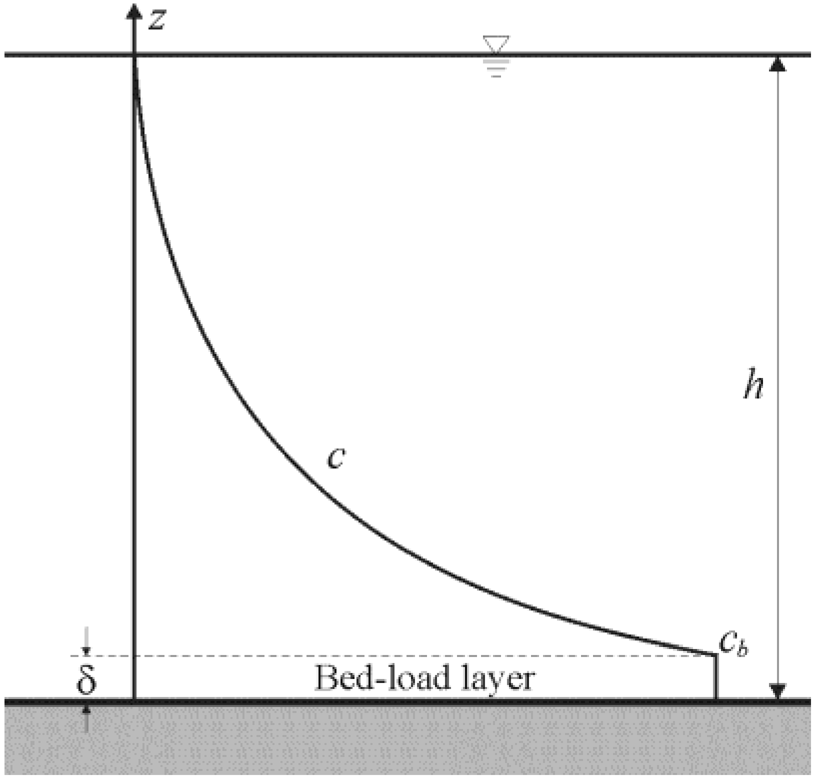
$$c_{*bk} = \frac{q_{*bk}}{\delta u_{bk}}$$

Bed-load layer thickness:

$$\delta = \max\left(2.0d_{50}, 0.5\Delta_r, 0.01h\right)$$

Bed-load velocity:

$$\frac{u_{bk}}{\sqrt{\left(\rho_s/\rho - 1\right) g d_k}} = 1.64\left(\frac{\tau_b'}{\tau_{cri,k}} - 1\right)^{0.5}$$



$$c_{*bk} = \frac{0.0032}{\delta} p_{bk} d_k \left(\frac{\tau'_b}{\tau_{cri,k}} - 1\right)^{1.7}$$

$$\tau_b' = \sqrt{\tau_{b,c}'^2 + \tau_{b,wm}'^2 + 2\tau_{b,c}'\tau_{b,wm}'\cos\varphi}$$

Suspended-load transport is determined by integrating the product of current velocity and suspended-load concentration over the flow depth:

$$q_{sk} = \int_{\delta}^{h} c_k u dz$$

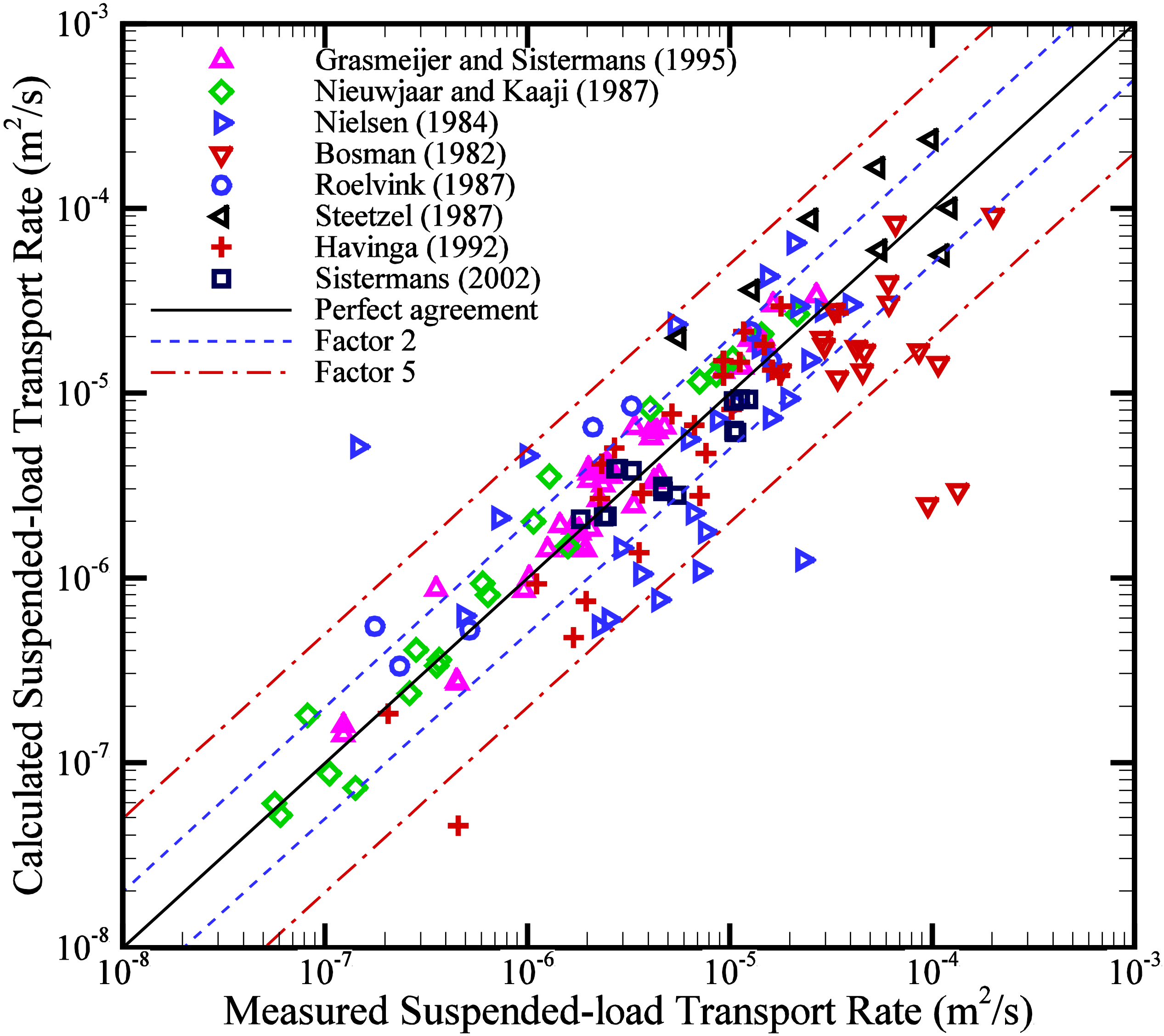
The current velocity is determined with van Rijn's two-layer log law, and the suspended-load concentration is by (Williams et al., 1999)

$$\frac{c_k(z)}{c_{bk}} = \left(\frac{z + L\alpha_{wc,k}}{\delta + L\alpha_{wc,k}} \right)^{-\alpha_{wc,k}}$$

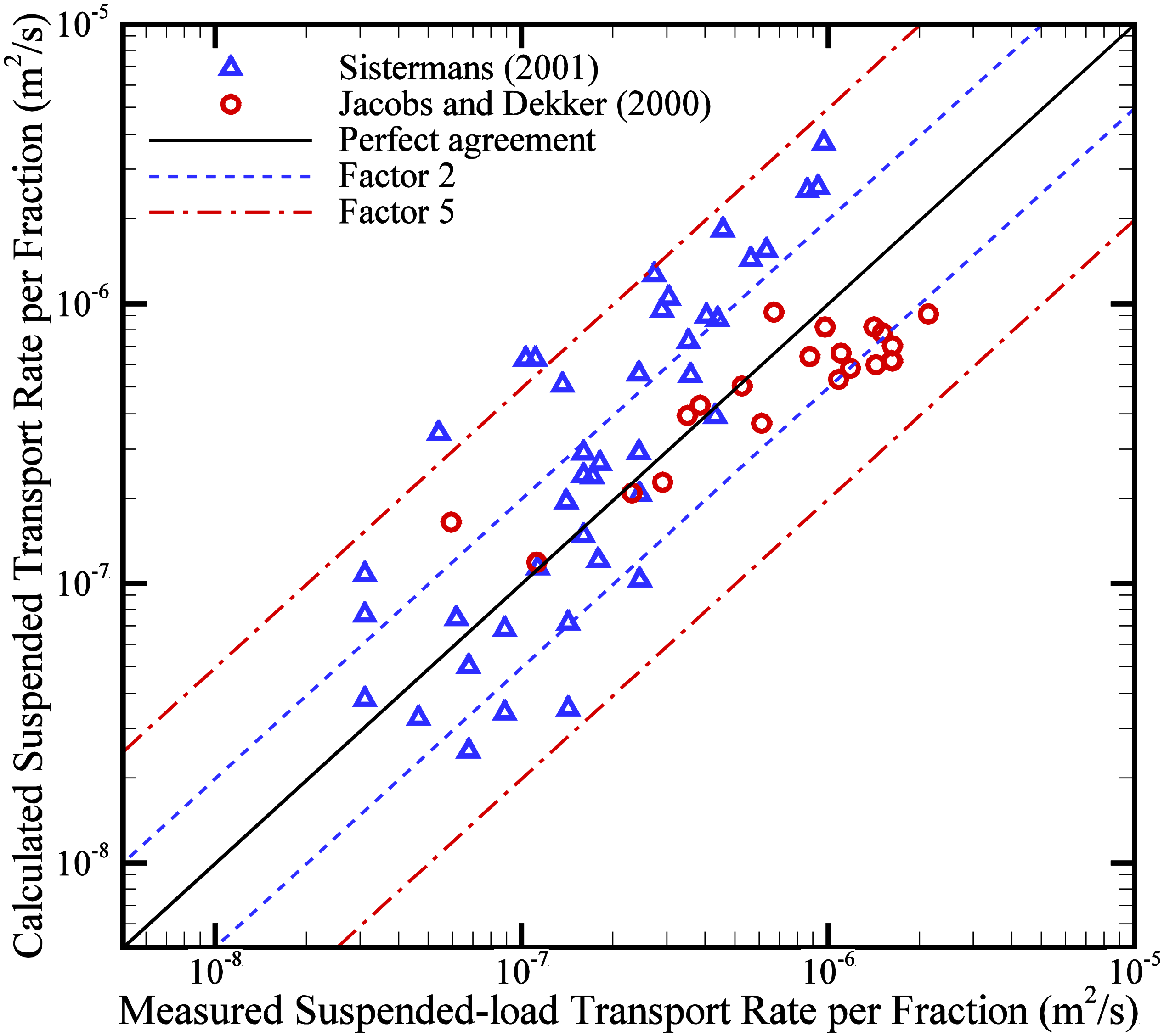
$$\alpha_{wc} = \omega_s \Big/ \left[\kappa \left(\overline{U}_{*wcR} + U_{*wG} \right) \right]$$

where $\overline{U}_{*wcR}$ is the time-averaged bed-shear velocity for ripple-scale roughness; U_{*wG} is the peak wave-only bed-shear velocity for grain-scale roughness; and L is coefficient defined by Nielsen (1992).

Transport rate by Near-bed Concentration of Uniform Suspended-Load



Fractional Transport rate by Near-bed Concentration of Nonuniform Suspended-Load



Summary

- Methods have been developed or selected to determine the bed shear stress under current and waves, in order to apply the existing Wu et al. (2000) formula for multiple-sized sediment transport in coastal water.
- The enhanced Wu et al. bed-load formula can calculate the onshore and offshore bed-load transport rates separately and then derive the net transport rate, whereas the enhanced suspended-load formula calculates only the net transport rate due to the limited available data.
- The near-bed suspended-load concentration at the reference level is related to bed-load transport rate, velocity and layer thickness.
- The developed formulas have been tested using the single-sized sediment transport data sets compiled by Camenen and Larson (2007) and several sets of nonuniform sediment transport data collected from literature. More than half of the test cases are predicted within a factor of 2 of the measured values. This accuracy is generally acceptable for sediment transport, particularly under current and waves.
- It is found that the measurement data of multiple-sized sediment transport under current and waves are quite limited. Only six sets of experiments on graded bed load and two on graded suspended load have been collected from literature. More experiment studies on graded sediment transport under current and waves are needed.

Publications Related

W. Wu and S. S.Y. Wang (1999). "Movable bed roughness in alluvial rivers," J. Hydraulic Eng., ASCE, 125(12), 1309–1312.

W. Wu, S.S.Y. Wang, and Y. Jia (2000). "Nonuniform sediment transport in alluvial rivers," J. Hydraulic Research, IAHR, 38(6), 427–434.

W. Wu and S. S. Y. Wang (2006). "Formulas for sediment porosity and settling velocity," J. Hydraulic Eng., ASCE, 132(8), 858–862.

W. Wu (2007), Computational River Dynamics, Taylor & Francis, UK, 494 p.

W. Wu and Q. Lin (2014). "Nonuniform sediment transport under non-breaking waves and currents." Coastal Engineering, 90, 1–14, http://dx.doi.org/10.1016/j.coastaleng.2014.04.006 0378-3839.