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Preface

The mechanics of sediment transport involves the study of sediment transport under the action of flow. It is an important part of the hydraulic science and is mainly related to the problems of engineering safety such as sediment deposition in reservoirs and the erosion of downstream river channels. The operation of a reservoir changes the flood process of natural rivers and the extremely low discharge in dry seasons, which mitigates potential water disasters into beneficial uses. In recent years, due to the large-scale development and application of water conservancy projects and the rapid economic development, the nutrients and pollutants in the water bodies have increased substantially, and the flow condition also deviates more and more from the natural state. The basic law of the coupled transport of these substances and sediment is the theory and method of environmental sediment. The research on environmental sediment mainly concerns the influence of sediment particles on chemical constituents to ensure the safety of water quality (see the monographs of D. M. DiToro and Hongwei Fang). Moreover, microorganisms such as bacteria, algae, and fungi adhere to the sediment particle surfaces to form biofilms. Generally, epilithic biofilm will form at bed surfaces where they are irradiated by the sun, and bacterial biofilms will form at bed surfaces at large water depths. On the one hand, biofilm growth changes the physical laws of sediment transport; on the other hand, it also affects the environmental and ecological processes in the water and at the bed surface. These changes should be the main components of eco-fluvial dynamics, and this book mainly discusses the effects of biofilm growth on sediment transport.

There are several key issues in the study of biofilm-coated sediment (hereafter referred to as bio-sediment) transport. First, bio-sediment not only experiences chemical flocculation but also biological flocculation. The resultant particle size is much larger than that of individual original sediment particles, and the density and morphology also will greatly change. Second, the bed surface of bio-sediment is different from that of the original sediment, in the aspects of bedform and resistance characteristics. Correspondingly, the transport characteristics of suspended sediment and bed sediment will be changed. Therefore, this book considers the flocculation characteristics of bio-sediment, and the suspended load and bedload are classified following traditional fluvial dynamics to determine the sediment transport properties after biofilm growth.

In this book, Chap. 1 describes the surface morphology, the heterogeneous surface charge distribution, and the adsorption/desorption characteristics of natural sediment particles (focusing on the research mainly completed by Dr. Lei Huang, Dr. Minghong Chen, and Dr. Zhihe Chen). Chapter 2 describes the change of surface morphology and density of sediment particles due to biofilm growth and also analyzes the microbial community in the bio-sediment (Dr. Huiming Zhao and Dr. Yishan Chen). Chapter 3 proposes a biomass dynamic model and discusses the bedform on the bio-sediment bed and the resistance to flow as well as the turbulence characteristics (Dr. Yishan Chen and Dr. Wei Cheng). Chapter 4 describes the bedload transport of bio-sediment, including the rheological properties, the incipient velocity, and the bedload transport rate (Dr. Huiming Zhao, Dr. Qianqian Shang, and Dr. Mehdi Fazeli). Chapter 5 describes the suspended load transport of bio-sediment, including the biological flocculation, the settling velocity, and the suspended load transport rate (Dr. Haojie Lai, Dr. Qianqian Shang, and Dr. Mehdi Fazeli). The sixth chapter discusses laboratory experiments of bio-sediment transport using a recirculating flume and also proposes mathematical models of bio-sediment transport based on the foregoing basic theories (Dr. Mehdi Fazeli, Dr. Huiming Zhao, Dr. Haojie Lai, and Dr. Wei Cheng). The whole book is written by Hongwei Fang and Lei Huang.

About ten years of our study of bio-sediment transport is summarized. Every Ph.D. student, the aforementioned persons, under my guidance, gradually added their research into a theoretical framework, thus forming a systematic research work. I thank these students for their hard work and good cooperation with me. The study of bio-sediment transport is an interdisciplinary subject involving many basic theories and extensive applications. Now the relevant research is still in its infancy, and it is difficult to present a systematic and comprehensive introduction of the theoretical framework. Thus, there have been certain defects and shortcomings in the process of compiling this book, and your comments and suggestions are highly appreciated.

Review comments by Steve Melching and suggestions by Danny Reible have led to an improved manuscript, although I bear the responsibility for any errors or shortcomings that remain.

Beijing, China Hongwei Fang
November 2019

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Notation[1]

A	Cross-sectional area (of particle)
AB	A coefficient representing the comprehensive effects of both aggregation and breakage on compaction
A_{bwm}	Effective Hamaker constant for the system of bacteria, water, and mineral
A_i	Interface area between two particles
A_p	Surface area of particles
Ar	Archimedes number, i.e. $gD_f^3\left(\rho_f - \rho\right)\rho/\mu^2$
$>Al–OH_2^+$	Surface functional group of corundum
$>Al–OH_2–RCOOH^+$	Attached bacteria on the surface of corundum
A_0, $\{a_n\}$, $\{b_n\}$	Fourier coefficients
A_{s0}, $\{a_{sn}\}$, $\{b_{sn}\}$	Normalized Fourier coefficients by the mean radius, R_{mean}, of sediment
a_h and b_v	Distances of the vertical and horizontal forces to the rotation point for the rolling of particles
$a - i$	Gray values for the neighboring grid cells in Fig. 1.10
$a_x' - i_x'$	First-order derivatives related to x for the neighboring grid cells in Fig. 1.10
$a_y' - i_y'$	First-order derivatives related to y for the neighboring grid cells in Fig. 1.10
a' and b'	$a' = -\ln a$ and $b' = -b$ in Eq. 2.20
a_0 and m_0	Parameters in the equation of bio-sediment size
a_1–a_5	Coefficients in Eqs. 4.24 and 4.25
a_p	Constant related to particle shape in Eq. 1.29
a_r	Reference level $z = a_r$
a_s	Calibration parameter in the formula of shear breakage frequency, $s_{i,s}$ (Eq. 5.23)
B	Biomass

[1]The following symbols are used in this book.

B_0	Minimal biomass
B_a	Active part of biomass
B_{acc}	Biomass accumulation in the sediment layer
B_b	Active bacterial density
B_i	Inactive part of biomass
B_{mean}	Mean value of biomass along the vertical direction
B_t	Total biomass in the Capdeville biofilm growth model (Eq. 3.4)
B_{w}	River (flume) width
$B(z)$	Biomass at the vertical location z
$B_b(z)$	Active bacterial density at the vertical location z
b_i	Concentration of ith biomass in the multi-species composite biofilm model (Eq. 3.5)
C	Chézy coefficient
C'	Chézy coefficient related to bio-sediment roughness
C_0, C_1, C_2	Capacitances of the corresponding layers for the electrical double layer (EDL)
C_A	Adhesion coefficient
C_A'	$C_A' = a_5\ C_A$ where a_5 is a coefficient
C_C	Cohesive coefficient ($=9.06 \times 10^{-5}/((\rho_{\mathrm{s}} - \rho)\ D^2)$)
C_D	Drag coefficient
C_{D0}	Drag coefficient of original sediment
C_{Df}	Drag coefficient of bio-sediment
C_L	Lift coefficient ($=\eta\ C_D$)
$C_{\max}$	Adsorption capacity, i.e. the maximum adsorption amount in Eq. 1.36
C_{s}	Adsorption amount per gram of sediment
C_{w}	Aqueous concentration of adsorbate at equilibrium
c	The total mass concentration
$c(s, t)$	Correlation function between the small image $w(x, y)$ and the large image $g(x, y)$ at the given position (s, t)
c_{auto}	Auto-detachment coefficient of biomass
c_{cat}	Catastrophic detachment coefficient of biomass
c_{det}	Chronic detachment coefficient of biomass
c'_{det}	Bacterial detachment coefficient
cellsize	Grid spacing in Eqs. 1.13 and 1.14
D	Sediment particle diameter
D_*	Dimensionless D, i.e. particle parameter
D_0	Original sediment size
D_1 and D_2	Diameters of the interacting bacterial cell and particle (or the interacting particles)
D_{50}	Median sediment size
D_b	Deposition rate
D_f	Floc/bio-sediment size

D_i	Mean diameter of the sediment particles of size class i for the calculation of S_{Vm} in Eq. 2.12
D_x	Diameter for which x percent of the particles are finer, e.g. D_{25}, D_{75}, D_{80}, D_{84}, and D_{90}
d	Pore size of sediment particles
d_f	Fractal dimension
d_{fi}	Fractal dimension of class i
$d_{f,\max}$	Maximum fractal dimension
E, F and G	Basic quantities of the first kind as the coefficients of the first basic form of the surface in Eq. 1.6
E_b	Entrainment rate
$\hat{E}_D$	Non-dimensional TKE dissipation rate (ε) as scaled by h/U_*^3
E_x	Diffusion coefficient
e	Electron charge
$\mathbf{F}_{Ci}$	Conservative force representing the non-bonding potential and bonding forces that irreversibly connect particles
$\mathbf{F}_{fp}$	Average information of Lagrangian particles
$\mathbf{F}_i$	Force exerted on each of the aggregated particles (i = 1, …, N_a)
$\mathbf{F}_s$	Force exerted on the single particle
F	Faraday's constant (=96485.34 C/mol)
F_1	Flocculation intensity
F_A	Adhesive force
F_b	Buoyancy force
F_C	Cohesive force
F_D	Drag force
F_f	Frictional force
F_G	Gravity force
F_{Gi}	Gravity force per unit volume
F_i	Forces acting on the cantilever of EFM
F_L	Lift force
F_r	Resistance force
F_y	Floc strength
Fr	Froude number ($=U/\sqrt{gh}$)
F_{ku}	Non-dimensional TKE flux in the longitudinal direction ($=f_{ku}/U_*^3$)
F_{kw}	Non-dimensional TKE flux in the vertical direction ($=f_{kw}/U_*^3$)
$\mathbf{f}_{\mathrm{col}}$	Inter-particle contact force
$\mathbf{f}_{fp}$	Fluid–particle interaction force
f	Friction coefficient
$f(\mathbf{r}, t)$	Particle distribution function

$f(S)$, $f(N)$, $f(I)$, and $f(T)$	Functions representing the effects of substrata, nutrients, illumination, and temperature on biofilm growth
$f(x, y)$	A continuous function
$f_{\text{flood}}(Q)$	Catastrophic detachment function for biofilm growth
f_{ku}	Turbulence kinetic energy flux (TKE flux) in the longitudinal direction $\left(= 0.5\left(\overline{u'u'u'} + \overline{u'w'w'}\right)\right)$
f_{kw}	Turbulence kinetic energy flux (TKE flux) in the vertical direction $\left(= 0.5\left(\overline{u'w'w'} + \overline{w'w'w'}\right)\right)$
G	Turbulent shear rate
G_p	Production of turbulent kinetic energy
G_x	First-order derivative of the continuous function $f(x, y)$ relative to x
G_y	First-order derivative of the continuous function $f(x, y)$ relative to y
G^{AB}	Lewis acid–base interaction energy
G^{EL}	Electrical double layer interaction energy
G^{LW}	Lifshitz–van der Waals attractive energy
G^{Tot}	Total interaction energy
g	Gravitational acceleration
g_i	A function describing the gain or loss of biomass
$g(x, y)$	A large image of $M \times N$ for the PTV measurement (image matching)
$\bar{g}(x, y)$	Mean value of $g(x, y)$ in the overlying region with $w(x, y)$
$g_e(w_{zb})$	A function of erosion representing the influence of sediment erosion rate on the biofilm development
H_M	Mean curvature of the surface
H	Hole size (or threshold) that draws a clear distinction between the strong events outside the hole and the weak ones inside it
H_{bm}	Separation distance between the bacterial cell and sediment particle
H_{min}	Minimum separation distance between two surfaces (=1.57 Å)
H_{ts}	Separation distance between the EFM tip and sample
h	Water depth
h_a	Atmospheric pressure measured by height of water column
$h_b(z)$	A function of the vertical location representing the linear distribution of biofilm development
I	Illumination intensity
I_m	Moment of inertia of the particle
I_s	Ionic strength

i_t	Threshold of the pixel values for the black–white binarization
$\mathbf{J}_i^b$	Flux of ith biomass in the multi-species composite biofilm model (Eqs. 3.5 and 3.6)
$\mathbf{J}_j^{SN}$	Flux of jth nutrient in the multi-species composite biofilm model (Eqs. 3.5 and 3.6)
J	Bed slope
J_N	Diffusion flux of nutrients at the biofilm–liquid interface
K	Floc carrying capacity for hosting the biomass $(=\beta_K(L^3 - V))$
K_B	Boltzmann constant ($=1.38 \times 10^{-23}$ J/K)
K_d	Partition coefficient representing the partitioning of adsorbates between the particulate and dissolved phases
K_F	Freundlich adsorption constant
K_G	Gaussian curvature of the surface
K_L	Langmuir adsorption constant related to the affinity of adsorbent to the adsorbate
K_M	Mass transfer coefficient
$K_n(x)$	Kirkwood function defined as Eq. 1.47
K_R	Mean value of the curvatures at each point of the cross section
K_S	Half-saturation coefficient for mass transfer
K^app	Apparent surface complexation constant
K^int	Intrinsic surface complexation constant
K_{a1}^int and K_{a2}^int	Intrinsic acidity constants
KHnx and KHpx	Half-saturation constants for the absorption of nitrogen and phosphorus during microbial growth
k	Turbulent kinetic energy (TKE), i.e. $0.5\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$
k_0, k_i, and k_j	Fitting coefficients in Eq. 4.4
k_a	Aggregation rate
$k_a{}'$	Dimensionless aggregation parameter
k_B	Half-saturation coefficient of biomass for active bacteria growth
k_b	Breakage rate
$k_b{}'$	Dimensionless breakage parameter
k_D	Inverse half-saturation coefficient for sediment size
k_e	Electrostatic constant ($=8.9880 \times 10^9$ Nm^2/C^2)
k_eff	Effective force constant for the EFM cantilever
k_I	Half-saturation coefficient for illumination
$k_{\mathrm{inv},B}$	Inverse half-saturation coefficient for biomass
$k_{\mathrm{inv},Bb}$	Inverse half-saturation coefficient for active bacterial density
k_m	Coefficient in the expression of $u_\mathrm{bottom} = k_m U_*$
k_N	Half-saturation coefficient for nutrients

k_{p1} and k_{p2}	Principal curvatures (i.e. the maximum and minimum normal curvatures, respectively)
k_s	Equivalent roughness height ($=k_s' + k_s''$)
k_s'	Roughness due to particles (i.e. skin friction)
k_s''	Roughness due to bedforms (i.e. form-drag friction)
k_s^+	Dimensionless roughness height ($=U_* k_s/\nu$)
k_{sp}	Spring constant for the EFM cantilever representing the ability to resist elastic deformations
k_*	Empirical coefficient in the expression of sediment carrying capacity, S_*
L	(Characteristic) floc size
L_i and L_j	Sizes of interacting particles
L_p	Primary particle size
L_s	Non-equilibrium adaptation length for bedload transport
L, M, N	Basic quantities of the second kind as the coefficients of the second basic form of the surface in Eq. 1.8
$l(i, j)$	Element in the *link* matrix that reflects the relations of particles in adjacent images
M and N	Number of rows and columns of the image pixels in Eq. 1.1
m	Mass of particles
m_i and a_i	Coefficients in Tang's (1963) equation of incipient velocity
$m_1 - m_4$	Constants in the expression of interface area between two particles (Eq. 4.22)
m_*	Empirical exponent in the expression of sediment carrying capacity, S_*
$\mathrm{mag}(\nabla f)$	Magnitude of the first-order derivative of the continuous function $f(x, y)$ at the point (x, y)
N	Nutrient concentration
N_0	Positive pressure between particles
N_b	Types of biomass in the multi-species composite biofilm model (Eqs. 3.5 and 3.6)
N_{DLVO}	Dimensionless parameter that characterizes the interaction energy for unfavorable deposition ($=\kappa A_{\mathrm{bwm}}/\varepsilon_0 \varepsilon_r \Psi_b \Psi_m$)
$N_{\mathrm{GRAY}}(i)$	Number of pixels with a pixel value of i
N_i	Number concentration of flocs of class i
N_l	Number of particles positioned within a certain distance l from the original stationary particle
N_{m}	Number of measurements
N_p	Number of discrete point charges on the particle surface
N_{SN}	Types of nutrients in the multi-species composite biofilm model (Eqs. 3.5 and 3.6)

NH_4, NO_3, and PO_4d	Concentrations of ammonium nitrogen, nitrate nitrogen, and dissolved phosphate
n	Number of the Fourier series (or number of terms of k_i and k_j in Eq. 4.4)
n_F	Adsorption constant
n_i	Number of the present ions per unit volume
n_M	Manning coefficient
n_R	Exponent in the rheological model
$n_{\tau y}$, n_μ, and $n_{\tau e}$	Fitting term of τ_y, μ, and τ_e in Eqs. 4.5 and 4.6
P	Nitrogen pressure
P_0	Saturated vapor pressure at liquid nitrogen temperature
P_D	Pressure energy diffusion rate
$\hat{P}_D$	Non-dimensional P_D as scaled by h/U_*^3
P_M	Pressure in the momentum equation (Eq. 6.9)
$P_n^m(\cos\theta)$	Associated Legendre function
p and q	First-order derivatives of $Z = Z(x, y)$ (i.e. $p = \partial Z/\partial x$ and $q = \partial Z/\partial y$)
p_0 and p_1	Probability of class occurrence with pixel values of $0 - i_t$ and $i_t + 1 - 255$, respectively
p'	Pressure fluctuation
$p(i)$	Percentage of pixels with a pixel value of i
Q	Flow discharge
Q_c	Critical discharge for catastrophic detachment
Q_{cl}	Quality factor of the cantilever
Q_r	Reaction quotient of surface adsorption
q_1 and q_2	Surface charges of the interacting bacterial cell and particle, respectively, in Eq. 1.53
q_a	Bedload transport rate at reference level $z = a_r$
q_b	Bedload transport rate
q_{bx}	Bedload in the x-direction
q_{by}	Bedload in the y-direction
q_{b*}	Equilibrium bedload transport rate
q_i	Discrete charge value at (r_{si}, θ_i, φ_i)
q_l	Discharge per unit width of the tributary or lateral inflow
q_s	Suspended load transport rate
q_{surf}	Surface charges of the sample for EFM measurement
q_{sx}	Suspended load in the x-direction
q_{sy}	Suspended load in the y-direction
q_{tip}	Surface charges of the tip for EFM measurement
$\hat{q}$	Maximum mass transfer rate
R	Particle radius
R^2	Coefficient of determination
R_u	Universal gas constant (=8.31 J/(mol K))

R_{Ba}	Growth rate of active biomass B_a in the Capdeville biofilm growth model
R_{Bi}	Growth rate of inactive biomass B_i in the Capdeville biofilm growth model
R_{Bt}	Growth rate of total biomass B_t in the Capdeville biofilm growth model
R_b	Hydraulic radius
R_b'	Hydraulic radius related to the particle size
Re	Reynolds number
Re_*	Particle Reynolds number for bed sediment ($=U_*D/\nu$) or for settling bio-sediment ($=\omega_f D_f/\nu$)
Re_*'	Roughness Reynolds number ($=U_*k_s/\nu$)
R_{mean}	Mean radius of a sediment particle
$R(\theta)$	Periodic function of radius representing the closed curve of particle edge profile
$R_s(\theta)$	Normalized periodic function of radius by the mean radius, R_{mean}, of sediment in the polar coordinates
$R_s(\theta, \varphi)$	Corresponding polar radius, $R_s(\theta)$, at the latitude of φ
$R_{s1}(\theta, \varphi)$ and $R_{s2}(\theta, \varphi)$	Calculated $R_s(\theta, \varphi)$ along the longitudinal and latitudinal directions, respectively
$\mathrm{R{-}COOH^0}$	Surface carboxyl group of bacteria
$\mathbf{r}$	Lattice site
r, s, t	Second-order derivatives of $Z = Z(x, y)$ (i.e. $r = \partial^2 Z/\partial x^2$; $s = \partial^2 Z/\partial x \partial y$; $t = \partial^2 Z/\partial y^2$)
r_j	A function describing the gain or loss of nutrients
(r_p, θ)	Polar coordinate
(r_s, θ, φ)	Spherical coordinate
S	Sediment concentration
S_*	Sediment carrying capacity
S_2	Sediment concentration at the first grid point above the bed of $z' = z_2'$
S_a	Reference concentration at the reference level $z = a_r$
S_b	Volumetric concentration of sediment in the bed layer
S_{bm}	Maximum volumetric concentration of sediment in the bed layer
S_{b*}	Equilibrium sediment concentration of the bed layer
S_B	Concentration of the biomass fraction ($=\Omega\ S$)
S_f	Friction slope
S_{inlet}	Sediment concentration at the beginning of the flume
S_{max}	Maximum sediment concentration along the flume
S_N	Concentration of nutrients in the reaction–diffusion kinetic model (Eq. 3.1)
S_{Nb}	Concentration of nutrients in the biofilm phase of the boundary layer

S_{Nj}	Concentration of jth nutrient in the multi-species composite biofilm model (Eqs. 3.5 and 3.6)
S_{Nl}	Concentration of nutrients in the liquid phase of the boundary layer
S_{outlet}	Sediment concentration at the end of the flume
S_S	Concentration of the sediment fraction (=(1−Ω)·S)
S_{Vm}	Limiting concentration of non-uniform particles (=0.92 − 0.2lg$\sum \Delta p_i/D_i$)
$S(z)$	Vertical distribution of volumetric concentration of sediment
$S_{i,H}(\hat{z})$	Fractional contribution from the event E_i (i = 1, 2, 3, or 4) toward RSS production
>S	Surface atom of sediment
$>SL^-$	Adsorbed anions on sediment surface
>SOH	Surface hydroxyl group of sediment
$>SOM^+$	Adsorbed metal cations on sediment surface
s	Relative density of sediment (=ρ_s/ρ) or bio-sediment (=ρ_f/ρ)
s_i	Breakage rate of particle class i
$s_{i,s}$	Breakage rate of particle class i induced by fluid shear rate
$\mathbf{T}_i$	Total torque acting on the particle
$\mathbf{T}_{\mathrm{col}}$	Torques resulting from the inter-particle contact force
$\mathbf{T}_{fp}$	Torques resulting from the fluid–particle interaction force
T	Temperature or absolute temperature
T_*	Transport stage parameter $\left(=\left(U_*^{\prime 2}-U_{*c}^2\right)/U_{*c}^2\right)$
T_{0B}	Reference temperature with the maximum specific growth rate of biomass (or optimal temperature for biofilm growth)
T_{0Bb}	Reference temperature with the maximum specific growth rate of active bacteria (or optimal temperature for active bacterial growth)
T_D	Turbulent kinetic energy (TKE) diffusion rate
$\hat{T}_D$	Non-dimensional T_D as scaled by h/U_*^3
T_F	Period of a periodic function in the polar coordinate for Fourier analysis
T_N	Non-spherical curvature of the surface
T_p	Turbulent kinetic energy (TKE) production rate
$\hat{T}_p$	Non-dimensional T_p as scaled by h/U_*^3
T_s	Sampling duration for the analysis of conditional RSS distributions
t	Time
t_{zb}	Time corresponding to the bed surface of z_b

$\mathbf{U}_a$	Unidirectional velocity of all the aggregated particles
$\mathbf{U}_f$	Fluid velocity
$\mathbf{U}_{pi}$	Particle velocity (i represents the ith particle)
$\mathbf{U}_s$	Translational velocity of the single particle
U	Average flow velocity of cross section
U_c	Incipient velocity
$U_{c,t}$	Incipient velocity of sediment with biofilm cultivation period of t
$U_{c,t=0}$	Incipient velocity of sediment with biofilm cultivation period of t = 0 (i.e. no biofilm cultivation)
U_*	Friction velocity (shear velocity)
U_*'	Shear velocity related to particles (bio-sediment roughness)
U_{*c}	Critical shear velocity
U_{*s}	Friction velocity derived from the energy slope
$U_{*\tau}$	Friction velocity derived from the distribution of Reynolds shear stress $(=\sqrt{\tau_0/\rho})$
u	Time-averaged flow velocity in the streamwise direction
u_a	Effective velocity at reference level $z = a_r$
u_b	Bio-sediment velocity in the streamwise direction
u_{bottom}	Bottom velocity (i.e. velocity at a distance of D from the bed)
u_i (i = 1, 2, 3)	Reynolds-averaged velocity components in directions x_i (i = 1, 2, 3)
$u_{\max}$	Maximum velocity (i.e. velocity at the water surface)
u_{pi}	A simplified set of particle velocities at a lattice node (i represents the direction of velocity vector)
u_r	Bio-sediment velocity relative to the flow $(=\sqrt{(u-\dot{x})^2+\dot{z}^2})$
u', v', w'	Turbulent velocity fluctuations in the longitudinal, lateral, and vertical directions
V	Volume of floc or bio-sediment
V_B	Volume of the biomass fraction in the floc/bio-sediment
V_g	Pore volume of sediment particles
V_{g1}, V_{g2}, and V_{g3}	Unavailable, optimal, and available pore volume of sediment particles
V_p	Volume of particles
V_S	Volume of the sediment fraction in the floc/bio-sediment
v	Kinematic viscosity coefficient
v_{BS}	Ratio of the volumes of biofilm and sediment ($=V_B/V_S$)
v_D	Viscous diffusion rate
v_t	Eddy viscosity
$\mathbf{W}_i$	Einstein's white noise term
W_B	Weight of the biofilm part of a bio-sediment particle

W_S	Weight of the sediment part of a bio-sediment particle
w_b	Bio-sediment velocity in the vertical direction
w_{bio}	Vertical penetration rate of biofilm
w_{zb}	Sediment erosion rate
$\bar{w}$	Mean value of $w(x, y)$
$w(x, y)$	A small image of $J \times K$ for the PTV measurement (image matching)
X	Population of a variable
X_f	Biofilm cell density
X_i	Measured values
$\bar{X}$	Average value of all measured data
$(X_1, X_2, X_3, \ldots X_n)$	A sample space of a variable
x, y	Location of pixels (or coordinate of points) of the 2D gray matrix $\boldsymbol{Z}(x, y)$
$\dot{x}$	Streamwise velocity of bio-sediment/biofloc
$\ddot{x}$	Acceleration of bio-sediment/biofloc in the streamwise direction
x_c, y_c	x-, y-coordinates of the center of mass of the sediment particle projection
Y_i	Simulated values
Y_j	Difference between the calculated surface potential and the initial guessed value, i.e. $Y_j = \Psi_0^* - \overline{\Psi_0(R, \theta, \varphi)}$
$\boldsymbol{Z}(x, y)$	2D matrix describing the gray image of sediment
Z	Water level
Z_{ij}	Pixel value of the 2D gray matrix, $\boldsymbol{Z}(x, y)$
Z_R	Rouse number $(=\omega_f/(\beta\kappa_v U_*))$
Z_R'	Modified Rouse number $(=Z_R + 2.5(\omega_f/U_*)^{0.8}(S_a/S_{bm})^{0.4})$
z	Vertical distance
z_0	Zero-velocity level or the roughness length
z_b	Elevation of the bed surface
z_i	Charge of the adsorbed positive/negative ions or valency of the present ions in the solution
z'	Distance from the bed surface, i.e. $z - z_b$
z_2'	Distance of the first grid point from the bed surface
$\dot{z}$	Vertical velocity of bio-sediment/biofloc
$\ddot{z}$	Acceleration of bio-sediment/biofloc in the vertical direction
$\hat{z}$	Scaled vertical distance $(=z/h$, or $(z + \Delta z_{vb})/h)$
Δ	Bedform height
Δ/λ	Bedform steepness
ΔG_{ad}	Gibbs free energy of surface adsorption reaction $(\Delta G_{\text{ad}} = \Delta G_{\text{int}} + \Delta G_{\text{el}} + RT\ln Q_r)$
ΔG_{el}	Electrostatic component of Gibbs free energy of surface adsorption reaction

ΔG_{int}	Chemical (intrinsic) component of Gibbs free energy of surface adsorption reaction
$\Delta G_{\text{adh}}^{\text{AB}}$	Acid–base (AB) component of the change in free energy
$\Delta G_{\text{adh}}^{\text{LW}}$	Lifshitz–van der Waals (LW) component of the change in free energy (Lifshitz free energy of adhesion)
Δp_i	Weight percentage of the sediment particles of size class i for the calculation of S_{Vm} in Eq. 2.12
ΔS_{De}	Change of suspended sediment concentration in the deposition region ($=S_{\text{outlet}} - S_{\max}$)
ΔS_{Er}	Change of suspended sediment concentration in the erosion region ($=S_{\max} - S_{\text{inlet}}$)
Δt	Computational time step
Δu	Relative velocity of flow with respect to the moving particle in the streamwise direction
Δz	Net change of surface charge due to species exchange that define the adsorption reaction
Δz_b	Bed deformation
Δz_{vb}	Depth of virtual bed from the bed surface
$\boldsymbol{\Delta}\phi_0$	Phase shift of the cantilever vibration for the surface charge measurement
∇f	First-order derivative of the continuous function $f(x, y)$
$\nabla^2 f$	Second-order derivative of the continuous function $f(x, y)$
∇p	Pressure gradient
α_s	Significance level
α	Restoring saturation coefficient
α'	Breakage probability due to collision
α_1	Coefficient of the roughness due to particle (=3 as suggested by van Rijn (1982))
α_2	Velocity coefficient ($=u_a/u_b$)
α_3	Volumetric shape factor ($=\pi/6$ for spheres)
α_{bx} and α_{by}	Directional cosines
α_D	$=\pi C_{Df}\rho D_f^2/8$
$\alpha_{i,\,j}$	Sticking efficiency between the particle classes i and j
α_L	Lift coefficient in Eq. 4.50
$\alpha_L{}'$	$=\alpha_L \rho v^{0.5} D_f^2 (\partial u/\partial z)^{0.5}$
α_m	Added mass coefficient to the bio-sediment mass (assumed to be 0.5 by van Rijn (1984a))
$\alpha_{m,n}$, $\beta_{m,n}$	Moments of surface charge distribution defined as Eqs. 1.48 and 1.49, respectively
β	A factor for diffusion of suspended sediment ($=1 + 2(\omega_f/U_*)^2$)
$\beta_1 - \beta_3$	Coefficients in the expression of adhesive force, $C_A{}'(t)$

β_{Bb}	Temperature dependence coefficient for active bacterial growth
β_I	Illumination dependence coefficient for biofilm growth
$\beta_{i,j}$	Collision frequency between the particle classes i and j
$\beta_{i,j}^{\mathrm{BM}}$	Collision frequency due to Brownian motion
$\beta_{i,j}^{\mathrm{DS}}$	Collision frequency due to differential settling
$\beta_{i,j}^{\mathrm{FS}}$	Collision frequency due to fluid shear
β_K	Proportionality coefficient
β_T	Temperature dependence coefficient for biofilm growth
Γ	Total surface charge of sediment
γ	Bulk density (specific weight) of water
γ_B	Bulk density of biofilm
$\gamma_{i,j}$	Breakage distribution function
γ_m	Constant in Eq. 1.48 (γ_m = 1 when m = 0; otherwise, γ_m = 1/2)
γ_s	Bulk density (specific weight) of sediment
$\gamma_s{}'$	Dry bulk density of sediment
$\gamma_{s\text{-M}}{}'$	Maximum dry bulk density of sediment
γ_{SB}	Bulk density of bio-sediment
$\gamma_{SB}{}'$	Dry bulk density of bio-sediment
$\gamma_{SB\text{-M}}{}'$	Maximum dry bulk density of bio-sediment
γ^{LW}	Lifshitz–van der Waals energy component of the surface tension, and $\gamma_{\mathrm{b}}^{\mathrm{LW}}$, $\gamma_{\mathrm{m}}^{\mathrm{LW}}$, and $\gamma_{\mathrm{w}}^{\mathrm{LW}}$ represent the value for bacteria, mineral, and water, respectively (or $\gamma_{\mathrm{s}}^{\mathrm{LW}}$ and $\gamma_{\mathrm{l}}^{\mathrm{LW}}$ represent the value for the solid and liquid, respectively)
γ^+	Electron acceptor parameter, and γ_{b}^+, γ_{m}^+, and γ_{w}^+ represent the value for bacteria, mineral, and water, respectively
γ^-	Electron donor parameter, and γ_{b}^-, γ_{m}^-, and γ_{w}^- represent the value for bacteria, mineral, and water, respectively
$\dot{\gamma}$	Steady (critical) strain rate in the rheological model
δ	Thickness of water molecules (=3 × 10^{-8} cm)
δ_B	Thickness of biofilm
δ_b	Thickness of bedload layer
δ_{ij} and δ_{j3}	Kronecker delta
δ_L	Thickness of viscous sub-layer (=$11.6\nu/U_*$)
$\delta_{\max}$	Maximum possible depth for biofilm growth
ε	Turbulent kinetic energy (TKE) dissipation rate
ε_0	Permittivity of a vacuum
ε_B	Volume ratio of biofilm to the total deposit
$\varepsilon_B{}'$	= $\ln[(\varepsilon_{B\text{-M}} - \varepsilon_B)/\varepsilon_B]$ in Eq. 2.20
$\varepsilon_{B\text{-M}}$	Maximum value of ε_B
ε_b	Porosity of the bottom sediment
ε_e	Permittivity of the electrolyte (aqueous medium)
ε_f	Fluid volume fraction

ε_m	Scale for the measurement of surface area and volume of particles
ε_p	Permittivity of the particle
ε_r	Relative permittivity of water
ζ	Biomass fraction of the floc volume ($=V_B/V$)
η	Flow parameter ($=\Theta/\Theta_c$)
η_d	Value of η corresponding to the maximum bedform steepness, $(\Delta/\lambda)_{\max}$
Θ	Shields number
Θ_c	Critical/threshold Shields number
Θ_{c0}	Noncohesive term of the critical Shields number for bio-sediment
Θ_{cC}	Cohesive term of the critical Shields number for bio-sediment
Θ_{cA}	Adhesive term of the critical Shields number for bio-sediment
θ	Inclination of riverbed
θ_l	Contact angle of the measuring liquid with mineral or bacteria
κ	Inverse Debye length, and κ^{-1} is the thickness of the electrical double layer (EDL)
κ_{v}	Von Kármán constant
κ_{BS}	Ratio of the bulk densities of biofilm and sediment ($=\gamma_B/\gamma_S$)
λ	Bedform length
λ_{BS}	Biofilm thickness ratio ($=\delta_B/D$)
λ_b	Saltation length of sediment
$\lambda_{i,\ H}(t)$	Detecting function in Eq. 3.32, i.e. $\lambda_{i,\ H}(t) = 1$ if the (u', w') pair is in quadrant i with $\lvert u'w' \rvert \geq H\sigma_u\sigma_w$, otherwise, $\lambda_{i,\ H}(t) = 0$
λ_{w}	Correlation length of water molecules in the liquid (i.e. gyration radius)
μ	Dynamic viscosity coefficient
μ_{app}	Apparent viscosity of non-Newtonian fluids
μ_B	Biomass growth rate
μ_{Bb}	Maximum specific growth rate for active bacteria
$\mu_{\max}$	Maximum specific growth rate for biomass
μ_p	Mean value of the population, X
μ_s	Mean value of the sample space, $(X_1, X_2, X_3, \ldots, X_n)$
ξ	Resisting moment per unit area due to the cohesion
ρ	Density of water/fluid
ρ_b	Density of biofilm
$\rho_b{}'$	Dry density of biofilm
ρ_f	Density of bio-sediment/biofloc
ρ_s	Density of sediment/primary particle ($=2650\ \mathrm{kg/m^3}$)

σ_0 and σ_1	Standard deviation of the class with pixel values of $0 - i_t$ and $i_t + 1 - 255$, respectively
σ_0, σ_β, σ_d	Surface charge of each plane for the electrical double layer (EDL)
σ_c	Turbulent Schmidt number
σ_F	Sum of the force derivatives for all the forces, F_i, acting on the EFM cantilever
σ_{KR}	Standard deviation of the curvatures at each point of the cross section
σ_p	Standard deviation of the population, X
σ_R	Standard deviation of the radius of the cross section
σ_s	Standard deviation of the sample space, $(X_1, X_2, X_3, \ldots, X_n)$
σ_u	Turbulence intensity in the longitudinal direction $(=\sqrt{\overline{u'^2}})$
$<\sigma_u>$	Relative turbulence intensity in the longitudinal direction
σ_w	Turbulence intensity in the vertical direction $(=\sqrt{\overline{w'^2}})$
$<\sigma_w>$	Relative turbulence intensity in the vertical direction
σ_L^2	Within-class variance
σ_J^2	Between-class variance
$\boldsymbol{\tau}_f$	Stress tensor
τ	Reynolds shear stress $(=-\rho\overline{u'w'})$
$\hat{\tau}$	Scaled Reynolds shear stress $(=\tau/\tau_0)$
τ_0	Bed shear stress $(=\rho U_*^2 = \gamma R_b S_f)$
τ_c	Incipient/critical shear stress
τ_{De}	Bed shear stresses in the deposition region
τ_{Er}	Bed shear stresses in the erosion region
τ_e	Stable shear stress in the rheological model
τ_{ij}	Turbulent shear stress calculated with the k-ε turbulence model
τ_R	Shear stress in the rheological model
τ_y	Yield stress in the rheological model
Φ	A function of particle size in Sha's (1965) equation of settling velocity
$\phi(t)$	Function represents the parameters $\tau_y(t)$, $\mu(t)$, or $\tau_e(t)$ in Eq. 4.4
$\phi(x, y)$	Direction of the first-order derivative of the continuous function $f(x, y)$ at the point (x, y), i.e. $\arctan(G_y/G_x)$
φ	sorting coefficient $(=(D_{75}/D_{25})^{0.5})$
χ	Einstein correction factor as a function of k_s/δ_L
Ψ_0	Electrostatic potential of the surface relative to the bulk solution
Ψ_0^*	Initial guessed value of surface potential relative to the bulk solution

$\Psi_0(R,\theta,\varphi)$	Distribution of the (calculated) surface potential
$\overline{\Psi_0(R,\theta,\varphi)}$	Average value of the (calculated) surface potential, $\Psi_0(R,\theta,\varphi)$
Ψ_0, Ψ_β, Ψ_d	Surface potential of each plane for the electrical double layer (EDL)
Ψ_b and Ψ_m	Surface potentials of the bacterial cell and mineral, respectively
ψ_i	Constraint forces that remain the distances within the aggregate unchanged
$\boldsymbol{\Omega}_s$	Rotational velocity of the single particle
Ω	Biomass fraction of the sediment concentration
Ω_a	A function of settling velocity in Sha's (1965) equation of settling velocity
$\Omega_i(f)$	Particle collision operator
$\boldsymbol{\omega}_{pi}$	Angular velocity of the particles (i represents the ith particle)
ω	Settling velocity
ω_0	Settling velocity of original sediment
ω_F	Frequency of the Fourier series
ω_f	Settling velocity of bio-sediment/biofloc
ω_i and ω_j	Settling velocities of interacting particles

Chapter 1
Surface Micro-morphology and Adsorption Properties of Sediment Particles

Biofilm growth on sediment is affected by the surface properties of sediment particles. Generally, sediment particles possess complex surface morphology, pores of various scales, and heterogenous surface charge distribution, which impact the adsorption of nutrients (pollutants) and attachment of bacteria on sediment, and further influence biofilm growth (Fang et al. 2009). Thus, this chapter first introduces the surface micro-morphology and charge distribution of sediment particles and their adsorption properties. That is, Sect. 1.1 describes the measurement and mathematical expression of surface micro-morphology; Sect. 1.2 presents the measurement and statistical analysis of the surface charge distribution; the adsorption properties and interactions between sediment and bacteria are discussed in Sect. 1.3. These concepts are the basis of the following chapters that explore biofilm growth and bio-sediment transport.

1.1 Surface Micro-morphology of Sediment Particles

1.1.1 Description of Surface Micro-morphology

The detailed characterization of sediment morphology is dependent on what one wants to learn, as different variables and indexes are required for different research objectives, and this characterization also is limited by the available instruments and methods. The diversification and refinement of characterization methods promote thorough studies of sediment morphology and increase understanding of smaller-scale problems. This sub-section gives a description of the characterization of surface morphology.

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1.1.1.1 Traditional Description Method

The study of sediment transport is based on the theory of Newtonian mechanics, which mainly considers the physical and macroscopic effects such as gravity, currents, waves, and wind. When describing the motion of an individual sediment particle, the sediment particle is generalized into a mass point or a geometry of a specific shape to characterize the behavior of actual particles. Therefore, the geometric properties of individual sediment particles mostly are described by one or two parameters. For example, the sediment particle size usually is characterized by its diameter. Because of the large range of sediment size, there are special definitions of particle diameter and the corresponding measurement methods, as listed in Table 1.1, and the definitions and calculation of nominal diameter, sieving diameter, and settling diameter commonly are used.

Moreover, the geometric features of sediment particles are generally described by roundness, sphericity, overall shape, and shape factor. Wentworth (1919) first proposed the concept of roundness to describe the sharpness of the edges and angles of particles, but roundness is difficult to apply to the projection of three-dimensional objects. Wadell (1932) improved the calculation of roundness and first defined sphericity as the ratio of the nominal diameter and the diameter of a circumsphere. The sphericity of this definition does not reflect the dynamics of particles in a fluid; Folk and Ward (1957) further proposed the concept of maximum projection sphericity, i.e. the ratio of the diameter of a sphere with the projected area the same as the minimum projected area of the particle and the nominal diameter. Similar to

Table 1.1 Concept and definition of particle size (Wang et al. 2002)

Physical quantities	Measuring method	Definition of particle size
Size of pebbles or gravel	Visualization, caliper, or gauge	Length, width, and thickness; and their arithmetic, geometric, or logarithmic mean values
Size of particle projection	Ruler or micrometer	Nominal projection diameter (the diameter of a circle with the same area as the projection)
Size of the transverse section of fine particles	Measuring in enlarged slice images with the foregoing methods	Slice diameter (the diameter of a circle with the same area as the slice)
Minimum area of transverse section	Sieving analysis	Sieving diameter (the minimum screen aperture that the particle can pass)
Mass	Balance	Diameter of a sphere with the same density and mass as the particle
Volume	Volume meter	Nominal diameter (the diameter of a sphere with the same volume as the particle)
Settling velocity	Settling cylinder, centrifuge, or sedimentation balance	Settling diameter (the diameter of a sphere with the same density and settling velocity as the particle)

the maximum projection sphericity, shape factor also is used to characterize the relation among the three axes of particles, representing the deviation of particles from standard shapes (Wettimuny and Penumadu 2004).

These methods of describing sediment particles are simply defined and have been widely used in traditional studies of sediment dynamics. However, they are subjected to greater limitations in the studies of sediment surface processes.

1.1.1.2 Fractal Dimension

Since the fractal theory was first put forward by Mandelbrot (1982), it has been widely applied to the study of complex geometry in nature, such as coastlines, river systems, terrain landforms, rock fractures, and even molecular structures. Pfeifer and Avnir (1983) found that many surfaces have self-similarity and self-affinity, i.e. fractal surfaces. Thus, fractal theory also is used to describe particles, such as rock, soil, protein, floc, and catalyst particles. The fractal method can describe not only the shape, but also the surface roughness and pore characteristics of particles, and there are different definitions of important particle features, such as the Hausdorff dimension, correlation dimension, information dimension, and capacity dimension (Xie 1991; Zhang 1995). There also are many methods to determine the fractal dimension, mainly the methods of yardstick (Mandelbrot 1982), gas adsorption (Avnir et al. 1984; Neimark 1990a; Yin 1991), thermodynamics (Neimark 1990b; Neimark and Unger 1993), mercury intrusion (Fu et al. 2001), small-angle X-ray diffraction (Tang et al. 2003), nuclear magnetic resonance (Kalumbu et al. 1996), and scanning electron microscopy (image method) (Chakraborti et al. 2000).

Fractal theory provides a powerful tool for describing the anisotropy of particles. In the past, it was mainly used to describe soil (Perfect and Kay 1995; Rice et al. 1999; Sokolowska and Sokolowski 1999; Dathe et al. 2001), activated carbon (Huang et al. 2000; Wang et al. 2006a), silica gel (Zhao 2003; Sheng et al. 2005), and mineral rock (Liu et al. 2005). Relatively few studies have been conducted on the application of fractal theory to sediment morphology. Chao et al. (1997) studied the surface fractal characteristics of sediment particles through the adsorption of emulsified oil and concluded a surface fractal dimension of 2.33. Li et al. (2003) studied the fractal surface of sediment by adsorption of adsorbate with different cross sections and modified the application of the Langmuir and Freundlich adsorption isotherms to fractal surfaces. Wang et al. (2005a) investigated the influence of temperature on fractal dimension using the nitrogen adsorption method. Wang et al. (2006b) found that the surfaces of sediment particles usually have multi-fractal properties under scales from nanometers to microns through image analysis, and there are some differences in the fractal dimension at different scales. It is believed that the fractal dimension obtained by image analysis is a description in a purely geometric sense for the surface roughness. In addition, there are also studies that applied fractal theory to the shape of sediment flocs (de Boer 1997; de Boer and Stone 1999; de Boer et al. 2000; Stone and Krishnappen 2005; Hong and Yang 2006).

The fractal method provides a method for describing sediment particles, which is more elaborate than traditional methods and can reflect more information on particle shape and surface structure, but there are still some limitations. For the same fractal dimension, the shape or surface structure of sediment particles can be significantly different, and the corresponding mechanical and chemical properties may also greatly differ. Thus, the fractal dimension cannot be used alone to describe the relation between particle morphology and other surface processes. Moreover, the surface fractal dimension based on image analysis is a description of surface roughness in a geometric sense which might be affected by the gray field. In contrast, the fractal dimension calculated by the methods of gas adsorption and yardstick is a measurement of a particle's surface-filling capacity, i.e. a higher accuracy.

1.1.1.3 Image Method

Fine sediment particles generally are of micron or millimeter size, and it is difficult to observe the surface morphology by eye. The rapid development of microscopic observation, image processing, and intelligence provides a convenient approach for morphologic study of fine particles. The commonly used microscopic equipment includes: scanning electron microscope (SEM) (Berkel and Beckett 1996), transmission electron microscope (TEM) (Hochella et al. 1999), atomic force microscope (AFM) (Buzio et al. 2003), environmental scanning electron microscope (ESEM) (Donald 2003; Zhao et al. 2011), energy-dispersive X-ray spectrometer (EDS) (Palumbo et al. 2001), and X-ray diffraction (XRD) (House and Denison 2002). The sample requirements are different for these different microscopic equipments, and the corresponding purposes of measurements also are very different.

Many scholars have made substantial effort on how to study the morphology and material properties of particles after acquiring images. For example, Chandan et al. (2004) described the texture, angularity, and shape of aggregates used in expressway construction through wavelet analysis, gradient operation, and shape factor and sphericity, respectively, and studied the relation between particle shape and aggregate properties. Wettimuny and Penumadu (2004) and Al-Rousan et al. (2007) described the shape of aggregates using the Fourier series method and defined the shape and roughness parameters to reflect different physical characteristics. Wang et al. (1982) analyzed SEM images of quartz using a statistical method and classified the shape, angularity, and texture into several groups through empirical parameters. Durian et al. (2006, 2007) studied the relation between the shape of broken rock and its transport process under experimental and natural conditions using the distribution of profile curvatures. In these studies, the grayscale gradient and Fourier series are effective methods for the study of sediment particle morphology.

Three-dimensional (3D) surface reconstruction based on the image method is an extension of particle morphology study. To reconstruct a 3D surface, images obtained from different light directions (ordinary optical imaging) or different