1

Introduction

Erosion and sedimentation refer to the motion of solid particles, called sediment. The natural processes of erosion, transportation and sedimentation, sketched in Figure 1.1, have been active throughout geological time and have shaped the present landscape of our world. Today, they can cause severe engineering and environmental problems.

Human activities usually accelerate the processes of erosion, transport, and sedimentation. For instance, soil erodibility is enhanced by plowing and tillage. The protective canopy is weakened by grubbing, cutting, or burning of existing vegetation. Besides producing harmful sediment, erosion may cause serious on-site damage to agricultural land by reducing the productivity of fertile soils. Under some circumstances, the erosion rate can be 100 to 1,000 times greater than the geological erosion rate of 0.1 ton/acre year (25 ton/km^2 year).

Severe erosion can occur during the construction of roads and highways when protective vegetation is removed and steep cut and fill slopes are left unprotected. Such erosion can cause local scour problems along with serious sedimentation downstream. Approximately 85% of the 571,000 bridges in the United States are built over waterways. The majority of these bridges span rivers and streams that are continuously adjusting their beds and banks. Bridges on more active streams can be expected to experience scour problems as a result of stream realignment. Local scour at bridge piers and erosion of abutments are the most common causes of bridge failure during floods.

Mining operations may introduce large volumes of sediment directly into natural streams. Mine dumps and spoil banks often continue to erode by natural rainfall for many years after mining operations have ceased. For example, some drainage and flood problems in the Sacramento Valley, California, as well as problems of construction and maintenance of navigation channels, can be traced directly to mining activities that took place more than a century ago at the time of the gold

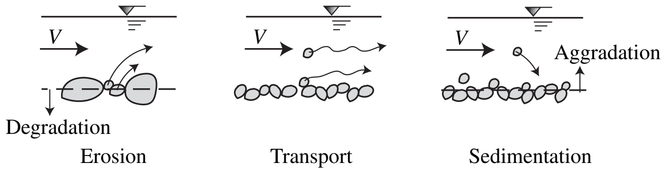


Figure 1.1. Processes of erosion, transport, and sedimentation

rush. Gravel stream mining can cause severe channel instabilities such as upstream headcutting, which may trigger instability problems at highway bridges.

Stream and river control works may have a serious local influence on channel erosion. Channel straightening, which increases slope and flow velocity, may initiate channel and bank erosion. If the bed of a main stream is lowered, the beds of tributary streams are also lowered. In many instances, such bed degradation is beneficial because it restores the flood-carrying capacity of channels.

Sediment transport affects water quality and its suitability for human consumption or use in various enterprises. Numerous industries cannot tolerate even the smallest amount of sediment in the water that is necessary for certain manufacturing processes, and the public pays a large price for the removal of sediments from the water it consumes every day.

Dam construction influences channel stability in two ways. It traps the incoming sediment, and it changes the natural flow and sediment load downstream. As a net result, degradation occurs below dams and aggradation might increase the risk of flooding upstream of the reservoir. Severe problems of abrasion of turbines, dredging, and stream instability and possible failure are often associated with reservoir and dam construction. Damage can be observed downstream from dam failure sites. In recent years, dam removal has become increasingly popular. The redistribution of sediment, at times contaminated, after dam removal will foster new research developments.

Sediment not only is the major water pollutant, but also serves as a catalyst, carrier, and storage agent of other forms of pollution. Sediment alone degrades water quality for municipal supply, recreation, industrial consumption and cooling, hydroelectric facilities, and aquatic life. In addition, chemicals and waste are assimilated onto and into sediment particles. Ion exchange occurs between solutes and sediments. Thus, sediment particles have become a source of increased concern as carriers and storage agents of pesticides, residues, adsorbed phosphorus, nitrogen, and other organic compounds, heavy metals, actinides and radioactive waste, as well as pathogenic bacteria and viruses.

The problems associated with sediment deposition are varied. Sediments deposited in stream channels reduce flood-carrying capacity, resulting in more frequent overflows and greater floodwater damage to adjacent properties. The

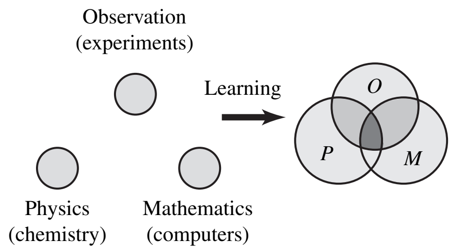


Figure 1.2. Learning erosion and sedimentation

deposition of sediments in irrigation and drainage canals, in navigation channels and floodways, in reservoirs and harbors, on streets and highways, and in buildings not only creates a nuisance but inflicts a high public cost in maintenance, removal, or in reduced services. Sedimentation is of vital concern in the conservation, development, and utilization of our soil and water resources.

As sketched in Figure 1.2, learning sedimentation involves three major elements: (1) observation; (2) physics and; (3) mathematics; these elements may seem disjointed at first. In the classroom, we develop the ability to: (1) make good observations; (2) understand the mechanics of the problem; and (3) find appropriate engineering solutions. Competence is developed through the skills in these three areas. The course CIVE716 aims at developing observational skills through a field trip and the analysis of laboratory and field data. Physical understanding is promoted through the in-depth analysis of the equations governing sediment transport. The mathematical skills are also developed through multiple exercises, calculation examples, homework, and computer problems. Altogether, these skills are displayed in numerous case studies illustrating solutions to sedimentation engineering problems.

This book rests on Newtonian mechanics and integrates concepts from fluid mechanics and sediment transport theory. Chapter 2 outlines the physical properties of sediments and dimensional analysis. Chapter 3 presents the fundamental principles of fluid mechanics applied to sediment-laden flows. Chapter 4 explains the concept of lift force and describes the motion of single particles in inviscid fluids. Chapter 5 analyzes viscous fluids and explains the concept of drag force. Applications of the concept of turbulence to sediment-laden flows are summarized in Chapter 6. Chapter 7 extends the analysis of the beginning of motion of single particles to complex three-dimensional cases with applications to stable channel design. The complex topics of bedform configurations and resistance to flow are reviewed in Chapter 8. The general topic of sediment transport is divided into three chapters: bedload in Chapter 9, suspended load in Chapter 10, and total load in Chapter 11. Sedimentation is covered in Chapter 12 with emphasis on reservoirs.

2

Physical properties and dimensional analysis

The processes of erosion, transport, and deposition of sediment particles introduced in Chapter 1 relate to the interaction between solid particles and the surrounding fluid. This chapter describes physical properties of water and solid particles in terms of dimensions and units (Section 2.1), physical properties of water (Section 2.2) and of sediment (Section 2.3). The method of dimensional analysis (Section 2.4) is then applied to representative erosion and sedimentation problems.

2.1 Dimensions and units

The physical properties of fluids and solids are usually expressed in terms of the following fundamental dimensions: mass (M), length (L), time (T), and temperature ($T°$). The fundamental dimensions are measurable parameters which can be quantified in fundamental units.

In the SI system of units, the basic *units* of mass, length, time, and temperature are the kilogram (kg), the meter (m), the second (s), and the degree Kelvin (°K), respectively. Alternatively, the Celsius scale (°C) is commonly preferred with the freezing point of water at 0°C, and the boiling point at 100°C.

A newton (N) is defined as the force required to accelerate one kilogram at one meter per second squared. Knowing that the acceleration due to gravity at the Earth's surface g is 9.81 m/s^2, the weight of a kilogram is obtained from Newton's second law: $F = \text{mass} \times \text{g} = 1\ \text{kg} \times 9.81\ \text{m/s}^2 = 9.81\text{N}$. The unit of work (or energy) is the joule (J) which equals the product of one newton times one meter. The unit of power is a watt (W) which is a joule per second. Prefixes are used to indicate multiples or fractions of units by powers of 10.

$$\left.\begin{array}{ll} \mu(\text{micro}) & = 10^{-6} \\ \text{m}(\text{milli}) & = 10^{-3} \\ \text{c}(\text{centi}) & = 10^{-2} \end{array}\right\} \left\{\begin{array}{ll} \text{k}(\text{kilo}) & = 10^{3} \\ \text{M}(\text{mega}) & = 10^{6} \\ \text{G}(\text{giga}) & = 10^{9} \end{array}\right.$$

Table 2.1. *Geometric, kinematic, dynamic, and dimensionless variables*

Variable	Symbol	Fundamental dimensions	SI Units
Geometric variables (L)			
length	L, x, h, d_s	L	m
area	A	L^2	m^2
volume	$\forall$	L^3	m^3
Kinematic variables (L, T)			
velocity	V, v_x, u, u_*	LT^{-1}	m/s
acceleration	a, a_x, g	LT^{-2}	m/s^2
kinematic viscosity	v	L^2T^{-1}	m^2/s
unit discharge	q	L^2T^{-1}	m^2/s
discharge	Q	L^3T^{-1}	m^3/s
Dynamic variables (M, L, T)			
mass	m	M	1 kg
force	$F = ma, mg$	MLT^{-2}	1 kg m/s^2 = 1 Newton
pressure	$p = F/A$	$ML^{-1}T^{-2}$	1 N/m^2 = 1 Pascal
shear stress	$\tau, \tau_{xy}, \tau_o, \tau_c$	$ML^{-1}T^{-2}$	1 N/m^2 = 1 Pascal
work or energy	$E = F \bullet d$	ML^2T^{-2}	1 Nm = 1 Joule
power	$P = E/t$	ML^2T^{-3}	1 Nm/s = 1 Watt
mass density	ρ, ρ_s	ML^{-3}	kg/m^3
specific weight	$\gamma, \gamma_s = \rho_s g$	$ML^{-2}T^{-2}$	N/m^3
dynamic viscosity	$\mu = \rho v$	$ML^{-1}T^{-1}$	1kg/ms = 1Ns/m^2 = 1 Pas
Dimensionless variables (–)			
slope	S_o, S_f	–	–
specific gravity	$G = \gamma_s/\gamma$	–	–
Reynolds number	Re $= Vh/v$	–	–
grain shear Reynolds number	Re$_* = u_* d_s / v$	–	–
Froude number	Fr $= V/\sqrt{gh}$	–	–
Shields parameter	$\tau_* = \tau/(\gamma_s - \gamma) d_s$	–	–
concentration	C_v, C_w, C	–	–

For example, one millimeter (mm) stands for 0.001 m and one mega watt (MW) equals one million watts (1,000,000 W).

In the English system of units, the time unit is a second, the fundamental units of length and mass are respectively the foot (ft), equal to 30.48 cm, and the slug, equal to 14.59 kg. The force required to accelerate a mass of one slug at one foot per second squared is a pound force (lb) used throughout this text. The temperature in degree Celsius T°_C is converted to the temperature in degree Fahrenheit T°_F using $T^\circ_F = 32^\circ F + 1.8 T^\circ_C$.

Table 2.2. *Conversion of units*

Unit	kg, m, s	N, Pa, Watt
1 acre	$= 4046.87\ m^2$	
1 acre foot (acre-ft)	$= 1233.5\ m^3$	
1 atmosphere	$= 101{,}325\ kg/ms^2$	$= 101.3$ k Pa
1 Btu = 778 lb ft	$= 1055\ kg\ m^2/s^2$	= 1055 Nm
1 bar	$= 100{,}000\ kg/ms^2$	= 100 k Pa
1 °Celsius $= (T_F^\circ - 32^\circ)5/9$	= 1°K	
1 °Fahrenheit $= 32 + 1.8T_C^\circ$	= 0.555556°K	
1 day = 1 d	= 86,400 s	
1 drop	$= 61\ mm^3$	
1 dyne	$= 0.00001\ kgm/s^2$	$= 1 \times 10^{-5}$ N
1 dyne/cm^2	$= 0.1\ kg/ms^2$	= 0.1 Pa
1 fathom	= 1.8288 m	
1 fluid ounce	$= 2.957 \times 10^{-5} m^3$	
1 foot = 1 ft	= 0.3048 m	
1 ft^3/s	$= 0.0283\ m^3/s$	
1 gallon (U.S., liquid) (gal)	$= 0.0037854\ m^3$	
1 gallon per minute (gpm)	$= 6.31 \times 10^{-5} m^3/s$	
1 mgd = 1 million gal/day = 1.55 ft^3/s	$= 0.04382\ m^3/s$	
1 horse power = 550 lb ft/s	$= 745.70\ kg\ m^2/s^3$	= 745.7 W
1 inch = 1 in	= 0.0254 m	
1 in of mercury	$= 3386.39\ kg/ms^2$	= 3386.39 Pa
1 in of water	$= 248.84\ kg/ms^2$	= 248.84 Pa
1 Joule	$= 1\ kg\ m^2/s^2$	= 1 Nm = 1 J
1 kip = 1000 lb	$= 4448.22\ kg\ m/s^2$	= 4448.22 N
1 knot	= 0.5144 m/s	
1 liter = 1l	$= 0.001\ m^3$	
1 micron (μm)	$= 1 \times 10^{-6}$ m	
1 mile (nautical)	= 1852 m	
1 mile (statute)	= 1609 m	
1 Newton	$= 1\ kg\ m/s^2$	1 N
1 ounce	= 0.02835 kg	
1 Pa	$= 1\ kg/ms^2$	1 N/m^2
1 pint	$= 0.0004732\ m^3$	
1 Poise = 1 P	= 0.1 kg/ms	0.1 Pa·s
1 pound-force (lb)	$= 4.448\ kg\ m/s^2$	= 4.448 N
1 lb ft	$= 1.356\ kg\ m^2/s^2$	= 1.356 Nm
1 psf (lb per ft^2)	$= 47.88\ kg/ms^2$	= 47.88 Pa
1 psi (lb per in^2)	$= 6894.76\ kg/ms^2$	= 6894.76 Pa
1 pound-force per ft^3	$= 157.09\ kg/m^2s^2$	= 157.09 N/m^3
1 quart	$= 0.00094635\ m^3$	
1 slug	= 14.59 kg	
1 slug/ft^3	$= 515.4\ kg/m^3$	

Table 2.2 *(cont.)*

Unit	kg, m, s	N, Pa, Watt
1 Stoke = 1cm^2/s	= 0.0001 m^2/s	
1 metric ton	= 1,000 kg	
1 short ton (2 kip mass)	= 907.2 kg	
1 short ton = 2,000 lb (weight)	= 8900 kg m/s^2	8.9 kN
1 long ton (UK)	= 1016.05 kg	
1 Watt US (W)	= 1 kg m^2/s^3	1 W
1 yard (yd)	= 0.9144 m	
1 year (yr)	31,536,000 s	

Most physical variables can be described in terms of three fundamental dimensions (M, L, T). Variables are classified as geometric, kinematic, dynamic, and dimensionless variables as shown in Table 2.1. Geometric variables involve length dimensions only and describe the geometry of a system through length, area, and volume. Kinematic variables describe the motion of fluid and solid particles and these variables can be depicted by only two fundamental dimensions, namely L and T. Dynamic variables involve mass terms in the fundamental dimensions. Force, pressure, shear stress, work, energy, power, mass density, specific weight, and dynamic viscosity are common examples of dynamic variables. Several conversion factors are listed in Table 2.2.

2.2 Physical properties of water

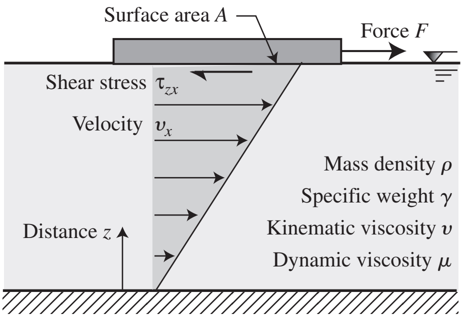
The principal properties of a nearly incompressible fluid like water are sketched on Figure 2.1.

Mass density of a fluid, ρ

The mass of fluid per unit volume is referred to as the mass density. The maximum mass density of water at 4°C is 1000 kg/m^3 and varies slightly with temperature as shown in Table 2.3. In comparison, the mass density of sea water is 1,025 kg/m^3, and at sea level, the mass density of air is $\rho_{air} = 1.2$ kg/m^3 at 0°C. The conversion factor is 1 slug/ft^3 = 515.4 kg/m^3.

Specific weight of a fluid, γ

The weight of fluid per unit volume of fluid defines the specific weight, described by the symbol γ (gamma). At 4°C, water has a specific weight $\gamma = 9810$ N/m^3 or



$$\tau_{zx} = \frac{F}{A} = \mu \frac{dv_x}{dz} = \rho v \frac{dv_x}{dz}$$

Figure 2.1. Newtonian fluid properties

62.4 lb/ft^3 (1 lb/ft^3 = 157.09 N/m^3). Specific weight varies slightly with temperature as given in Table 2.3. The specific weight γ equals the product of the mass density ρ times the gravitational acceleration $g = 32.2$ ft/s^2 = 9.81 m/s^2.

$$\gamma = \rho g \tag{2.1}$$

Dynamic viscosity, μ

As a fluid is brought into deformation, the velocity of the fluid at any boundary equals the velocity of the boundary. The ensuing rate of fluid deformation causes a shear stress τ_{zx} proportional to the dynamic viscosity μ and the rate of deformation of the fluid, dv_x/dz.

$$\tau_{zx} = \mu \frac{dv_x}{dz} \tag{2.2}$$

The fundamental dimensions of the dynamic viscosity μ are M/LT which is a dynamic variable. As indicated in Table 2.3, the dynamic viscosity of water decreases with temperature. Fluids without yield stress for which the dynamic viscosity remains constant regardless of the rate of deformation are called Newtonian fluids. The dynamic viscosity of clear water at 20°C is 1 centipoise: 1cP = 0.01 P = 0.001 Ns/m^2 = 0.001 Pas (1 lb·s/ft^2 = 47.88 Ns/m^2 = 47.88 Pas).

Kinematic viscosity, v

When the dynamic viscosity of a fluid μ is divided by the mass density ρ of the same fluid, the mass terms cancel out.

$$\mu = \rho v \tag{2.3a}$$

Table 2.3. *Physical properties of clear water at atmospheric pressure*

Temperature °C	Mass density ρ kg/m^3	Specific weight γ N/m^3 or kg/m^{2}s^2	Dynamic viscosity μ Ns/m^2 or kg/ms	Kinematic viscosity ν m^2/s
−30	921	9,035	Ice	Ice
−20	919	9,015	Ice	Ice
−10	918	9,005	Ice	Ice
0	999.9	9,809	1.79×10^{-3}	1.79×10^{-6}
4	1,000	9,810	1.56×10^{-3}	1.56×10^{-6}
5	999.9	9,809	1.51×10^{-3}	1.51×10^{-6}
10	999.7	9,809	1.31×10^{-3}	1.31×10^{-6}
15	999	9,800	1.14×10^{-3}	1.14×10^{-6}
20	998	9,790	1.00×10^{-3}	1.00×10^{-6}
25	997	9,781	8.91×10^{-4}	8.94×10^{-7}
30	996	9,771	7.97×10^{-4}	8.00×10^{-7}
35	994	9,751	7.20×10^{-4}	7.25×10^{-7}
40	992	9,732	6.53×10^{-4}	6.58×10^{-7}
50	988	9,693	5.47×10^{-4}	5.53×10^{-7}
60	983	9,643	4.66×10^{-4}	4.74×10^{-7}
70	978	9,594	4.04×10^{-4}	4.13×10^{-7}
80	972	9,535	3.54×10^{-4}	3.64×10^{-7}
90	965	9,467	3.15×10^{-4}	3.26×10^{-7}
100	958	9,398	2.82×10^{-4}	2.94×10^{-7}
°F	slug/ft^3	lb/ft^3	lb·s/ft^2	ft^2/s
0	1.78	57.40	Ice	Ice
10	1.78	57.34	Ice	Ice
20	1.78	57.31	Ice	Ice
30	1.77	57.25	Ice	Ice
32	1.931	62.40	3.75×10^{-5}	1.93×10^{-5}
40	1.938	62.43	3.23×10^{-5}	1.66×10^{-5}
50	1.938	62.40	2.73×10^{-5}	1.41×10^{-5}
60	1.936	62.37	2.36×10^{-5}	1.22×10^{-5}
70	1.935	62.30	2.05×10^{-5}	1.06×10^{-5}
80	1.93	62.22	1.80×10^{-5}	0.930×10^{-5}
100	1.93	62.00	1.42×10^{-5}	0.739×10^{-5}
120	1.92	61.72	1.17×10^{-5}	0.609×10^{-5}
140	1.91	61.38	0.981×10^{-5}	0.514×10^{-5}
160	1.90	61.00	0.838×10^{-5}	0.442×10^{-5}
180	1.88	60.58	0.726×10^{-5}	0.385×10^{-5}
200	1.87	60.12	0.637×10^{-5}	0.341×10^{-5}
212	1.86	59.83	0.593×10^{-5}	0.319×10^{-5}

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This results in the kinematic viscosity ν with dimensions L^2/T, which is also shown in Table 2.3 to decrease with temperature. The viscosity of clear water at 20°C is 1 centistoke = 0.01 cm^2/s = 1×10^{-6} m^2/s (1 ft^2/s = 0.0929 m^2/s).

$$v = \frac{1.78 \times 10^{-6} \mathrm{m}^2/S}{\left[1 + 0.0337\, T_C^o + 0.0002217\, T_C^{o2}\right]} \tag{2.3b}$$

It is important to remember that both the density and viscosity of water decrease with temperature. Comparatively, the kinematic viscosity of air is approximately 1.6×10^{-4} ft^2/s or about 1.6×10^{-5} m^2/s at 20°C and increases slightly with temperature.

2.3 Physical properties of sediment

This section describes the physical properties of sediment as: single particle (Section 2.3.1), sediment mixture (Section 2.3.2), and sediment suspension (Section 2.3.3).

2.3.1 Single particle

The physical properties of a single solid particle of volume $\forall_s$ are sketched on Figure 2.2.

Mass density of solid particles, ρ_s

The mass density of a solid particle ρ_s describes the solid mass per unit volume. The mass density of quartz particles 2,650 kg/m^3 (1 slug/ft^3 = 515.4 kg/m^3) does not vary significantly with temperature and is assumed constant in most calculations. It must be kept in mind, however, that heavy minerals like iron, copper, etc. have much larger values of mass density.

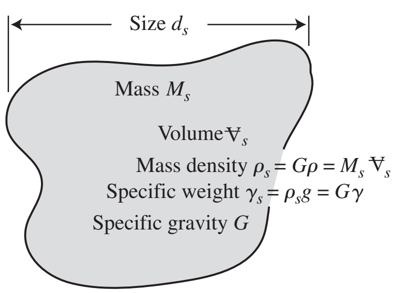

Figure 2.2. Physical properties of a single particle