CHAPTER 4

SEDIMENT MOVEMENT BY FLUID FLOW

4.1 FUNDAMENTALS OF FLUID FLOW

Introduction

Before discussing the transport and sorting of sediment and the formation of sedimentary structures, some attention must be given to the part of the dynamic environment often neglected by the geologist—the fluid. The term *fluid* includes both liquids and gases. A fluid is a substance that is deformed by a shear force, no matter how small the force may be; that is, it is a substance that has no strength.

The forces that act on solid or fluid bodies are vectors that may be resolved into components normal to and parallel with the surface of the body. The components of force, per unit area, normal to the surface are called *pressure*; those parallel to the surface are called *shear stress*. It is convenient to distinguish certain *body forces* that act equally on every particle composing the body—for example, gravity or inertia. Gases, including air, respond to change in pressure by expansion or contraction; that is, they are compressible fluids and, at high speeds, the density cannot be treated as constant. Liquids are only slightly compressible, however, and for a given temperature the density may be considered to be constant.

Apart from the density, the other main property of fluids controlling the way the fluid flows is the dynamic viscosity. As noted earlier, this is defined as the coefficient in the equation relating the shear stress acting on a fluid to its rate of shear. In many dynamic equations the ratio of dynamic viscosity to density (μ/ρ) appears, and this ratio is called the *kinematic viscosity* ν (nu). These parameters have dimensions as indicated in Table 3-4.

Air and water are the two fluids of greatest geological importance. They differ substantially in their density and dynamic viscosity with water being some 800 times as dense as air and having a much larger dynamic viscosity. At 20°C the dynamic viscosity of water is almost exactly 0.001 kg m^{-1} s^{-1}, which is about 55 times that of air. The kinematic viscosity of air (at 20°C) is, however, 15 times that of water (Fig. 4-1). Both air and water are fluids that obey Newton's law of viscosity:

$$\tau = \mu \frac{dU}{dy} \qquad (1)$$

For pure water or air, the dynamic viscosity μ is a constant at constant temperature (see Chap. 3). Water may, however, become mixed with substantial concentration of clays—for example, in mud flows. High concentrations of clay not only greatly increase the viscosity (Fig. 4-2) but also change the way in which the suspension responds to shear stress so that the coefficient of viscosity is no longer a constant. Such substances are described as *non-Newtonian fluids*.

At high sediment concentrations muds may acquire strength so that they can no longer be sheared by very low shear stresses. At shear stresses in excess of this strength such muds behave like viscous fluids. Substances that behave in this way are described as *pseudo-plastics*. Some of their properties are discussed further in Chap. 5.

The behavior of Newtonian fluids is described by the equations of fluid dynamics, based on Newton's law of viscosity and the laws of Newtonian dynamics. The basic equations are (a) the equation of *continuity*, which simply expresses the law of conservation of mass for a fluid, and (b) the three *Navier–Stokes* equations, or equations of motion, which express how Newton's dynamic laws must apply to a fluid. Together they make up a system of four partial differential equations that express, in principle, how a viscous fluid must behave in any and all circumstances in which Newtonian dynamics are valid.

The ideal explanation of any fluid phenomenon (including all sedimentation phenomena) is to show how the phenomenon may be deduced from the four equations, plus a statement about the shapes of the fluid boundaries (the "boundary conditions"). Nature is generally too complicated to permit the solution of these equations, although it can be done for a few simple cases, including the very slow movement of a sphere through a fluid. Here Stokes' law, discussed on p. 63, was actually derived from the basic equations of motion by Stokes in 1851.

Dimensionless Numbers

One very important application of the basic equations is to derive the proper criteria for making scale models of fluid flow that correctly represent phenomena

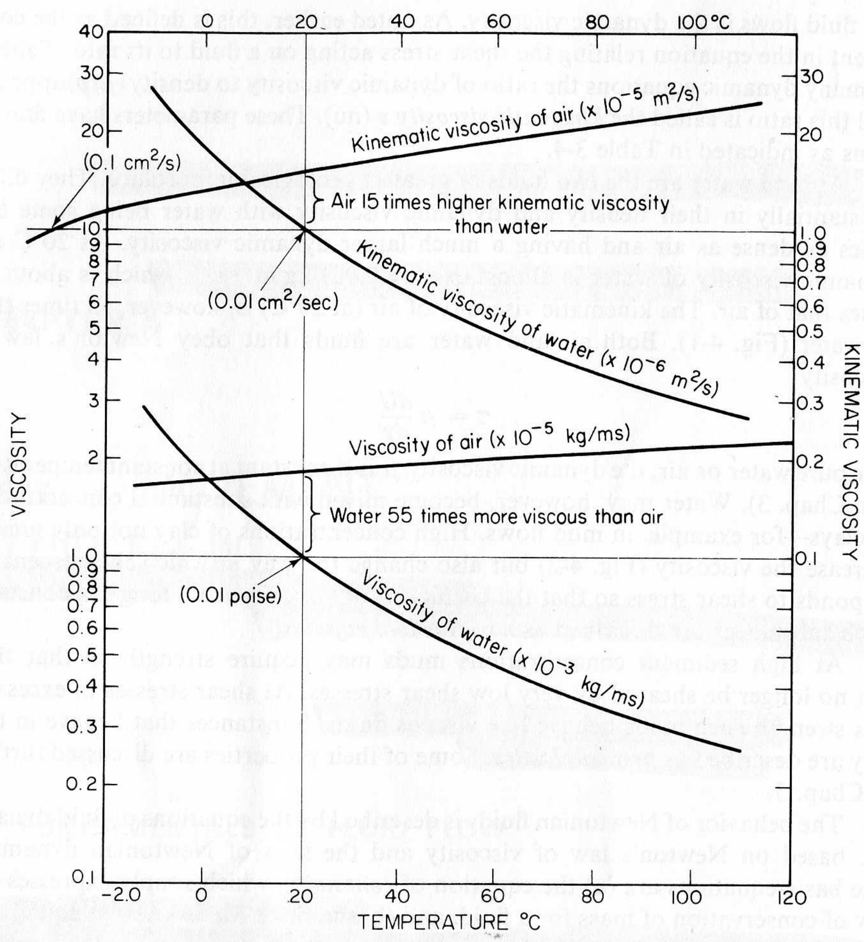

Fig. 4-1 Variation in dynamic and kinematic viscosity of air and water with temperature. (Scale for dynamic viscosity on left, for kinematic viscosity on right.)

at a different (usually larger) scale. In the equations, if we express all the lengths as ratios of some reference length, all velocities as ratios of some standard velocity, and the other variables similarly and then rearrange the terms, we find for the equations that apply to flow of fluids with a free surface subject to gravity that two coefficients appear (see Daily and Harleman, 1966). In other words, in order to make all the variables in the equations dimensionless (scaled in terms of some reference length L and velocity U), it is necessary to introduce two dimensionless coefficients:

$$R_e = \frac{UL\rho}{\mu} \quad \text{(Reynolds number)} \qquad (2)$$

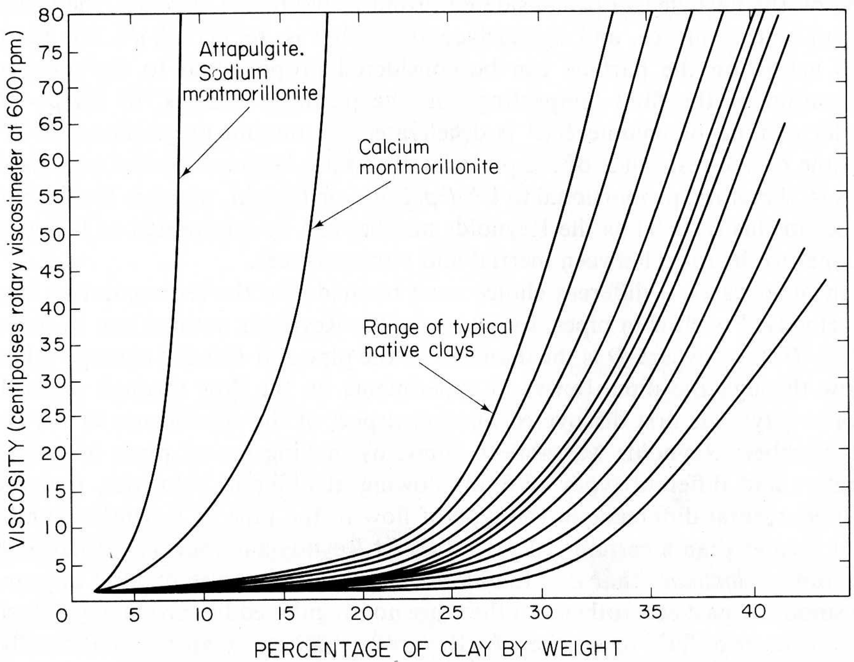

Fig. 4-2 Variation in dynamic viscosity of clay suspensions with clay concentration and mineralogy. (From Grim, *Applied Clay Mineralogy*, McGraw-Hill Book Co. After data in "Drilling Mud," Baroid Division National Lead Co., 1953.)

$$F_r = \frac{U}{\sqrt{gL}} \quad \text{(Froude number)} \tag{3}$$

This means that if there are two situations (the original or *prototype* and the *model*) that have the same shaped boundaries and if the Reynolds number and Froude number of the model are equal to the Reynolds number and Froude number for the prototype, then the two situations will be exactly similar as far as all aspects of the fluids are concerned. The only differences will be in the scale of the phenomena, not in their basic nature.

The derivation of Reynolds and Froude numbers sketched above cannot be given in detail here. It is the most fundamental way, however, to derive these two numbers that play a prominent part in the discussion of most hydraulic phenomena, including many aspects of sedimentation. The significance of the numbers can be illustrated by reference to some specific applications.

The *Reynolds number* appeared previously in the discussion of particle settling given on p. 61. In that case, the representative length L may be taken as the diameter of the particle d. It was observed experimentally that the drag force acting on the particle is a function of the Reynolds number. Only at low Reynolds numbers (less than unity) is the drag force correctly given by Stokes' law. The viscous force acting on the particle can be considered proportional to the viscosity, the velocity gradient at the surface, and the surface area—that is, to $\mu(U/d)\,d^2$. The inertial forces acting on the particle can be considered proportional to the mass and deceleration of the fluid "impacting" on the particle,—that is, to $Ud^2\rho \cdot U$ (a cylinder of fluid of volume $U\,d^2$ is decelerated an amount proportional to U in unit time by the resistance of the particle). The ratio between inertial and viscous forces is, therefore, proportional to $U^2\,d^2\rho/U\,d\mu$, or $U\,d\rho/\mu$, which is the Reynolds number in this case. Thus the Reynolds number can be interpreted as being proportional to the ratio between inertial and viscous forces.

In other cases, a different choice must be made for the representative length and velocity. For flow in pipes, for example, the Reynolds number can be defined as $R_e = UD\rho/\mu$, where D is the diameter of the pipe and U is the average velocity of flow through the pipe. It was in experiments on the flow through pipes that Osborne Reynolds first discovered another aspect of the significance of the Reynolds number. Reynolds was able to show, by making use of pipes of different diameters and different types of fluids flowing at different velocities, that there is a fundamental difference in the type of flow in the pipe at Reynolds numbers less or greater than a certain critical value. At Reynolds numbers less than about 2000, flow is *laminar*; that is, the different layers or particles of fluid appear to slide smoothly past each other and there are no irregular eddies producing diffusion from one layer of fluid to another. At Reynolds numbers greater than about 2000, however, flow is *turbulent* with eddies producing diffusion of fluid (and also of anything that is carried by the fluid, such as dye or sediment) from one layer to another.

The critical value of the Reynolds number for the transition from laminar to turbulent flow depends on the choice of representative length and velocity and on the geometry and some other properties of the flow system. In the case of flow past a settling spherical particle, flow is laminar and does not "separate" from the surface of the sphere up to a Reynolds number of 24. Above this value a wake filled by a single ring eddy is formed in the lee of the particle. The patterns of flow observed at progressively higher Reynolds numbers are shown in Fig. 4-3. At first the eddy in the wake has a regular geometry, but the eddy gradually becomes more irregular in nature until the wake is fully turbulent ($R_e > 1000$).

The *Froude number* is analogous to the Reynolds number in that it, too, can be considered a ratio between two types of forces: in this case, inertial and gravity forces. For a unit mass of fluid moving with a velocity U, the inertial force is equal to the force required to decelerate the mass to rest, in a distance that can be arbitrarily chosen as proportional to some characteristic length L. The time required is thus proportional to L/U; consequently, the rate of deceleration, or force acting on unit mass, is proportional to $U/t = U^2/L$. The gravity force acting on unit mass is equal to g; so the ratio of inertial to gravity forces is proportional to U^2/gL. The Froude number is defined by most engineers as the square root of this quantity—that is, $F_r = U/\sqrt{gL}$.

In the special case of water of depth D flowing in an open channel, the Froude

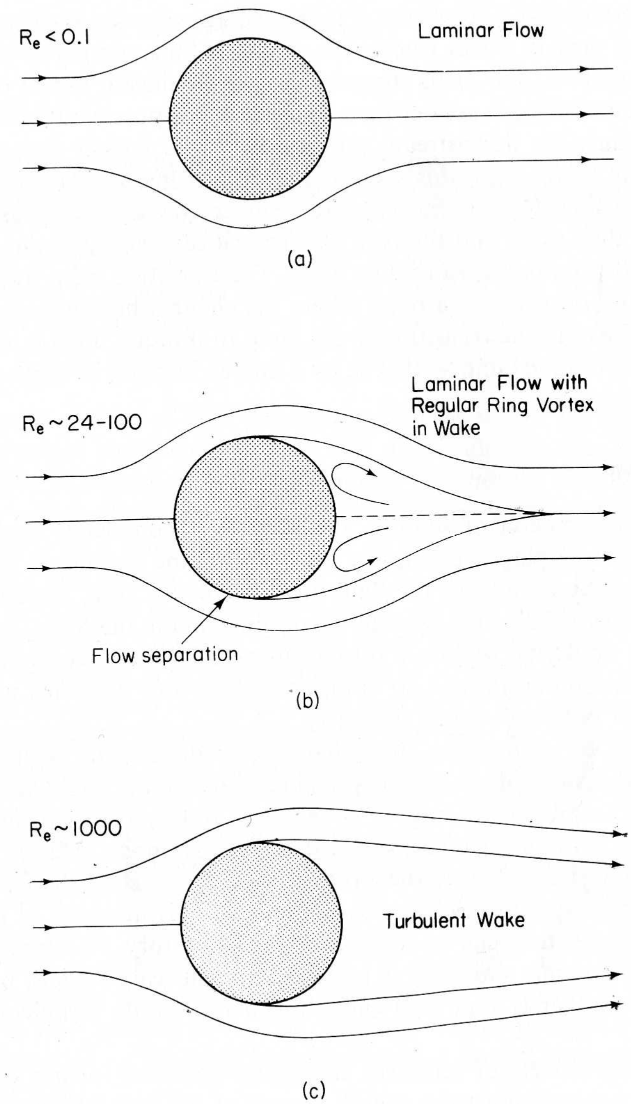

Fig. 4-3 Progressive development of a wake in the lee of a sphere with increasing Reynolds number (R_e) of the flow. (a) At $R_e < 0.1$, flow is laminar and drag on the sphere is dominated by viscosity. (b) Formation of a wake (by "flow separation") begins at $R_e = 24$. At first, flow within the wake remains laminar and consists mainly of a single, ring-shaped vortex, which becomes more elongate as R_e increases. At $R_e > 100$, the ring vortex becomes unstable. (c) At $R_e > 1000$, the wake becomes fully turbulent: the drag is due mainly to pressure distribution (inertial rather than viscous forces), and C_D is almost constant at a value of 0.4 (see Fig. 3-10).

number is therefore $U/\sqrt{gD}$, where U is the average velocity. It can be shown that the velocity of gravity waves whose wavelength is long compared with the depth of water is equal to $\sqrt{gD}$. This suggests another significant aspect of the Froude number: If the number is greater than unity, it is not possible for waves to travel upstream because the downstream velocity of flow is greater than the upstream velocity of the waves. For this reason, there are some fundamental differences in the type of flow (called *tranquil*, streaming, or subcritical) found at Froude numbers less than unity and the type of flow (called *rapid*, shooting, or supercritical) at Froude numbers greater than unity. The transition from tranquil to rapid flow (frequently observed at a point where the channel becomes steeper) may be smooth, but the opposite transition (from rapid to tranquil flow) is always accompanied by a "hydraulic jump"—that is, by a sudden increase in depth accompanied by much turbulence.

Scale Models

In the phenomenon of settling, the particle is completely enclosed by the fluid. The only role played by gravity is in causing the particle to move. Gravity does not affect the motion of the fluid directly. In this case, therefore, only the Reynolds number need be the same in the original and in the scale model for complete dynamic similarity. In flow in open channels all three forces (gravity, inertial, and viscous) are important and so both the Froude and Reynolds numbers must be the same for perfect dynamic similarity.

Clearly, if the length scale is to be changed, the Froude and Reynolds numbers can only be held constant by changing the properties of the fluid from the original to the model. In practice, doing so is generally not feasible, so models do not achieve perfect dynamic similarity. Experience has shown that it is generally much more important to scale the Froude number correctly than to attempt to scale the Reynolds number. In any case, the Reynolds numbers of large natural flows are far greater than can be achieved in the laboratory. Fortunately, a reasonable degree of dynamic similarity is possible in small-scale models, provided that the Reynolds number is kept high enough to achieve fully turbulent flow in the model.

In studying models of sediment transport, however, further complications arise. Ideally, not only must the overall aspects of the flow be correctly modeled but also the interaction of the flow and the sediment particles. In Sec. 4.4 it is shown that many different variables affect the interaction of the flow with the sediment; this interaction, in turn, affects the geometry of the channel boundaries so that true-to-nature small-scale models are almost never possible. The realization of this fact has led experimenters to construct very large models. For example, the large tilting flume operated by the U.S. Geological Survey at Fort Collins, Colorado, is 8 feet wide and about 200 feet long and very large wave channels are found in several hydraulics laboratories. Even the largest models cannot reproduce all the phenomena observed in nature.