

## Static Water in Soil

We now look at how water interacts with the solid system of the soil. In particular, we shall study surface tension, and then see how it is related to the rise and fall of water in soil pores, which, in turn, explains hysteresis.

### 6.1 SURFACE TENSION

We first recall the definitions of some terms from elementary physics (Kirkham and Powers, 1972, p. 11). An object is under tension if a pull is being exerted on it. In Figure 6.1, the cross-section  $A$  of the cylinder is

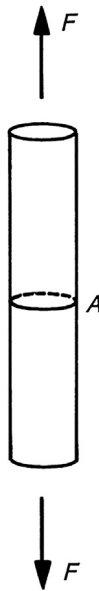


FIGURE 6.1 Illustration of tension. From Kirkham and Powers (1972). This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

under tension due to the forces  $F$ . Tension is a pull or stretching force per unit area. Pressure implies a push and is a compression force per unit area. If we reverse the directions of the arrows in Figure 6.1, the cylinder will be under pressure. In talking about soil water and plant water, we sometimes say that the water is under stress. Stress may be either a pull or a push, tension, or compression. So stress may properly be expressed as a pull or push per unit area.

The term *surface tension* should not be confused with tension (Kirkham and Powers, 1972, pp. 11–12). Surface tension, or more specifically, the surface tension coefficient, an energy per unit area, is equivalently a force per unit length, whereas tension is a force per unit area. We abbreviate the surface tension coefficient using the Greek letter sigma ( $\sigma$ ).

$$\sigma = \text{energy/area} = (\text{force})(\text{distance})/\text{area} \quad (6.1)$$

or

$$\sigma = \text{force/length}. \quad (6.2)$$

Surface tension may be compared with the force that develops in a sheet of paper when we pull it on opposite edges. In Figure 6.2, the force  $F$  when divided by the length  $AB$  gives a surface tension coefficient  $\sigma$ , which may be denoted by

$$\sigma = F/(2AB), \quad (6.3)$$

where the 2 in the denominator is used because the sheet of paper has an upper and a lower surface even though the paper is thin.

Laplace (1749–1827), a French mathematician and astronomer, explained surface tension. (See the Appendix, Section 6.4, for a biography of Laplace.) A molecule in the body of a fluid (Figure 6.3) is attracted equally from all sides. But a molecule at the surface undergoes a resultant inward pull because there are no molecules outside the liquid causing attraction. Hence, molecules in the surface have a stronger tendency to move to the interior of the liquid than the molecules in the interior have to move to the surface. What results is a tendency for any body of liquid to minimize its surface area. A molecule at the surface of a liquid is acted on

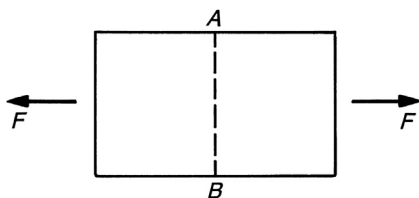


FIGURE 6.2 Surface tension in a sheet. From Kirkham and Powers (1972). This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

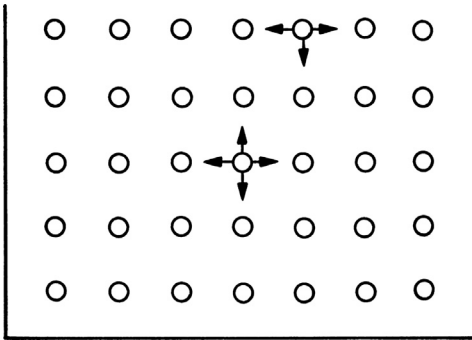


FIGURE 6.3 Laplace's surface tension theory. From *Kirkham and Powers (1972)*. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

by a net inward cohesive force that is perpendicular to the surface. So it requires work to move molecules to the surface against this opposing force, and the surface molecules have more energy than interior ones (Schaum, 1961, p. 108).

This tendency to minimize surface area is often opposed by external forces acting on the body of liquid, as gravity acting on a water drop resting on a flat surface, or as adhesive forces between water and other materials. Thus, the actual surface may not be an absolute minimum, but rather a minimum depending on the conditions in which the body of liquid is found (Kirkham and Powers, 1972, pp. 12–13).

The surface tension coefficient has been expressed as a force per unit length. If a wire is pulled horizontally from beneath a liquid, as illustrated in Figure 6.4, the force required to pull it out depends on the length of the wire. Let the symbols in Figure 6.4 be defined as follows:

- $F$  = upward pull required to balance surface tension forces (gravitational forces neglected);
- $L$  = length of wire;
- $\sigma$  = surface tension (units of force per unit length);
- $d$  = distance wire is raised.

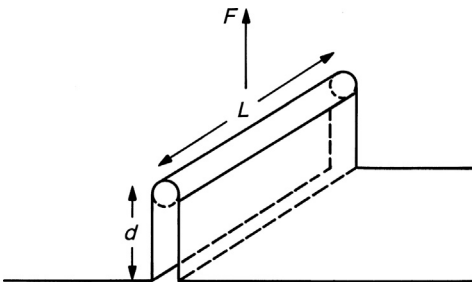


FIGURE 6.4 Wire being pulled from water with adhering water film. From *Kirkham and Powers (1972)*. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

Then we have

$$F = 2(\sigma L), \quad (6.4)$$

where the 2 is used because the force to be overcome by surface tension is developed on the two sides of the wire. (Note that the wire is circular, but water adheres to two “sides”.) Now the work  $W$  required to pull the wire against surface tension forces through the distance  $d$  is

$$W = Fd. \quad (6.5)$$

That is, using the relation  $F = 2(\sigma L)$ , we have

$$W = \sigma(2Ld) \quad (6.6)$$

or

$$\sigma = W/(2Ld) \quad (6.7)$$

or

$$\sigma = W/(\text{increased area of surface}). \quad (6.8)$$

That is,  $\sigma$  is the energy stored in the surface per unit increase in its area. So by pulling the wire out of a liquid, we can see that the coefficient of surface tension may be expressed as the energy stored per unit area of increase in the surface.

Surface tension causes the rise or fall of a liquid in a capillary tube. We are going to relate the rise of water in soil to the rise of water in capillary tubes, so we need to understand the rise of water in capillary tubes. The equation for the height of rise in a capillary tube,  $h$ , is (Schaum, 1961, p. 108)

$$h = (2\sigma \cos \alpha)/(r\rho g), \quad (6.9)$$

where

- $\sigma$  = surface tension of the liquid;
- $r$  = radius of the tube;
- $\rho$  = density of the liquid;
- $\alpha$  = contact angle between the liquid and tube (called the wetting angle in terminology used in soil science);
- $g$  = acceleration due to gravity.

We shall now prove this equation in a simple manner, recognizing that more complicated proofs exist using calculus (Porter, 1971; Sophocleous, 2010).

Let us look at Figure 6.5 (Schaum, 1961, p. 109). Consider the body of liquid inside the tube and above the outside level. The vertical (downward and upward) forces acting on it must balance. The downward force

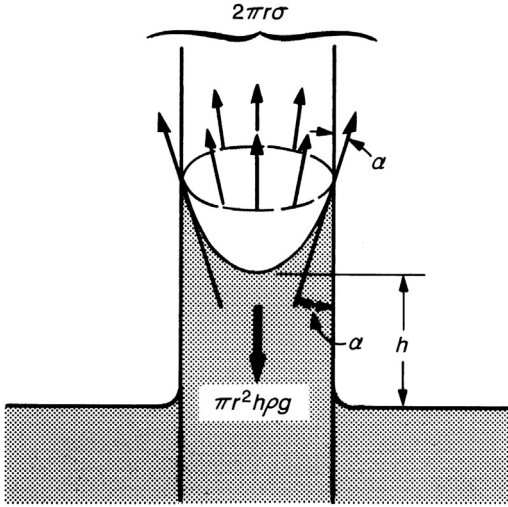


FIGURE 6.5 Height of rise of a liquid in a capillary tube. From [Schaum \(1961\)](#). This material is reproduced with permission of The McGraw-Hill Companies.

is its weight. Remember from Chapter 2 that weight,  $w$ , is a force and  $w = mg$ , where  $m$  is the mass and  $g$  is defined above.

weight of liquid inside tube = volume  $\times$  weight per unit volume

$$= \pi r^2 h \times mg/V = \pi r^2 h \times (m/V)g \quad (6.10)$$

$$= \pi r^2 h \rho g \text{ acting downward.} \quad (6.11)$$

The upward force is due to surface tension. Remember that surface tension,  $\sigma$ , is a force/length and the length of the tube is its circumference,  $2\pi r$ . The force is the perpendicular force, so to get the normal component, we must multiply  $2\pi r$  by  $\cos \alpha$ . So the upward force is  $2\pi r \sigma \cos \alpha$ , and this is the force due to surface tension. For vertical equilibrium,

upward force = downward force

$$2\pi r \sigma \cos \alpha = \pi r^2 h \rho g \quad (6.12)$$

or

$$h = (2\sigma \cos \alpha) / (r\rho g). \quad (6.13)$$

The meniscus in the capillary tube can be either convex or concave. (In physics, *meniscus* is defined as the curved upper surface of a column of liquid. It comes from the Greek word *meniskos*, which is a diminutive of *mene*, "the moon.") A convex meniscus is illustrated by mercury on glass and a concave meniscus is illustrated by water on glass ([Figure 6.6](#)). Mercury in contact with glass has an angle of contact of  $130^\circ$ – $140^\circ$  ([Porter,](#)

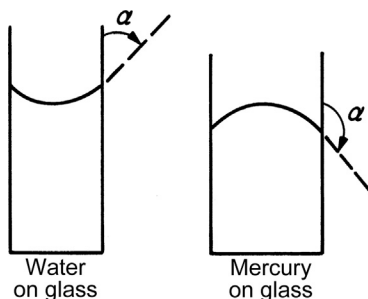


FIGURE 6.6 Angles of contact. From Kirkham and Powers (1972). This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

1971, p. 447). For water in contact with most soil minerals, the wetting angle,  $\alpha$  (also abbreviated  $\theta$ ), is close to zero (Linford, 1930), so in the equation for the height of rise in a capillary tube, we can take  $\cos 0 = 1$  or  $\cos \alpha = 1$ . However, in highly repellent soils, the contact angle is large.

Leon Linford (1930) developed a clever way to measure the wetting angle in soil by using mirrors and the well-known laws of reflection in physics. The angle of incidence is the angle between the incident ray and the normal to the reflecting surface at the point of incidence (Schaum, 1961, p. 214) (Figure 6.7). The angle of reflection is the angle between the reflected ray and the normal to the surface. The laws of reflection are the following: (1) The incident ray, reflected ray, and normal to the reflecting surface lie in the same plane. (2) The angle of incidence equals the angle of reflection. Concave mirrors form real and inverted images of objects located outside of the principal focus; if the object is between the principal focus and the mirror, the image is virtual, erect, and enlarged. Convex

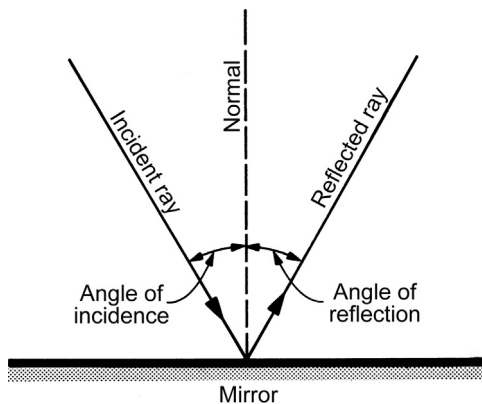


FIGURE 6.7 The angles of incidence and reflection. From Schaum (1961). This material is reproduced with permission of The McGraw-Hill Companies.

mirrors produce only virtual, erect, and smaller images. Linford (1930) beamed light down into soil and said,

Any point of the [water] meniscus, acting as a cylindrical concave mirror would reflect the light back and upwards at an angle such that it is twice the angle between the tangent to the meniscus at the point in question and the vertical. If the angle of contact is zero, the light reflected from the top of the meniscus would come back horizontally... [B]y photographing the reflected light, the angle of contact was shown to be very small if not zero.

Leon Linford, born July 8, 1904 (Cattell, 1955), was a physicist who worked at Utah State in Logan, Utah, and joined the famous Radiation Laboratory at the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts, during the Second World War (Buderi, 1996; Seitz, 1996). After the war, Linford became the Head of the Department of Physics at the University of Utah in Salt Lake City, but died of cancer in 1957 (Cattell, 1961), perhaps from exposure to radioactivity at the Radiation Laboratory.

## 6.2 EXAMPLES OF SURFACE TENSION

The importance of surface tension can be illustrated in five ways.

1. A water beetle or other small aquatic organisms can float on water because of surface tension (Porter, 1971, p. 442; Dickinson, 2003; Hu et al., 2003; Gao and Jiang, 2004). The fact that small insects can float on water shows the close relationship between the way they have evolved and water. (We remember from Chapter 2 that another example of the relationship between animal evolution and properties of water is the fact that water has a minimum specific heat at 35 °C.) One can simulate a water beetle by floating a razor blade on water. The razor blade will float on an unbroken water surface, but it will not float if the surface tension is broken by soap.
2. We can kill mosquitoes by putting oil on water. Because surface tension is broken and the mosquitoes cannot float, they sink and die. Just a little oil will do (Don Kirkham, personal communication, January 30, 1992).
3. Ducks cannot float as easily on a farm pond with oil as on a pond with no oil (Don Kirkham, personal communication, January 30, 1992).
4. Oil is put on ocean water to calm the waves (Don Kirkham, personal communication, January 30, 1992). For example, this might be done at shipwrecks. Familiar quotations allude to oil calming water. Plutarch (A.D. 46–120) said, “Why does pouring oil on the sea make it clear and calm? Is it for that the winds, slipping the smooth oil, have no force, nor

cause any waves?" (Bartlett, 1955, p. 49). Pliny the Elder (A.D. 23–79) said, "Everything is soothed by oil, and this is the reason why divers send out small quantities of it from their mouths, because it smooths every part which is rough" (Bartlett, 1955, p. 49). In 1757 on a journey to London, Benjamin Franklin (1706–1790; American statesman, scientist, inventor, and writer) observed that wakes of two ships were remarkably smooth, while others were ruffled by the wind. Seeking an explanation, he asked the captain, who told him that the cooks on those two ships had probably just emptied their greasy water. The captain thought it as a fairly stupid question since the answer was a common knowledge among seamen. Franklin, recollecting what he had read in Pliny, then resolved to carry out himself experiments on the effect of oil on water (Mertens, 2006). Water surfaces in nature are typically contaminated by surfactant films that alter the surface tension (Liu and Duncan, 2003).

5. Walnut shells clump together if floated on water. An experiment can be done in which half-shells of walnuts (with the nut meat removed) are used to make little boats floating on water. Put the walnuts in a pan of water—the walls of the pan must be clean (i.e., no soap or grease on the sides of the pan)—and the walnuts pull together by themselves in the small pan. They pull together to keep the surface energy to a minimum. The walnuts will form chains or trains as they clump together. Adding soap to the water would change the wetting angle and the walnuts would not clump together. As noted above, surface tension occurs in any body of liquid and causes the surface area to be minimized.

The walnuts in water simulate soil conditioners, which cause aggregation. There are many types of soil conditioners (Schamp et al., 1975; see their Figure 6.2 for polymers used as soil conditioners). Some of them have charged ions in the molecule (e.g., sodium polyacrylate with  $\text{Na}^+$  or K-polystyrene-sulfonate with a  $\text{K}^+$ ), but many of them have no charged ions in their molecular structure. The popular polyacrylamide (PAM), widely used as a soil conditioner (see the cover of the 1998 November–December issue of the *Soil Science Society of America Journal*, and the accompanying article by Sojka et al., 1998), comes in a nonionic form (Aly and Letey, 1988). For these nonionic polymers, hydrogen bonding may not be as important in binding the polymers to water and soil and helping in aggregation as it would be for ionic polymers. The nonionic soil conditioners probably have an effect like the walnuts; they minimize the surface energy of water in the soil. Marcel De Boodt, who got his Master's Degree at Iowa State University, said (personal communication, 1976) that his career was based on the simple walnut demonstration, which Don Kirkham showed in his soil physics class. Professor De Boodt built a



world-famous laboratory focusing on soil conditioners at the University of Ghent, Belgium. The laboratory had projects around the world and utilized soil conditioners to stabilize the sands around landing strips at airports in oil-wealthy desert countries in the Middle East and Africa. Soil conditioners such as sand, clay, peat, and cinders have been used for a long time. The new, commercial chemical soil conditioners were introduced about 1950. The Monsanto Chemical Company supplied one called krilium, a maleic acid of a vinyl acetate polymer (Kirkham and Runkles, 1952). The use of soil conditioners has been limited by their cost. The water-soluble anionic form of PAM is used today as a soil conditioner in agriculture to reduce erosion and manage infiltration in furrow irrigations. In furrow-irrigation trials in Idaho, USA, use of PAM increased yields of corn (*Zea mays* L.) by 4.5% and bean (*Phaseolus vulgaris* L.) by 14.3%, which indicated that the cost of PAM applications may be recoverable (Lentz and Sojka, 2009). Chemical soil conditioners were used to stabilize the slopes of a canal in Ghent, Belgium; plantings along the canal then could be established and the beautification work won a prize (Don Kirkham, personal communication, February 10, 1994). De Boodt (1975) and Wallace and Terry (1998) review soil conditioners.

Many other examples concerning the importance of surface tension could be given, such as the following: two pennies or two thin pieces of glass stick together with water between them; leaf waxes make water roll off leaves; chemicals are put on raincoats to waterproof them so water droplets will run off them; and adjuvants are added to herbicides so they can more readily be absorbed by plant leaves. Drifting small particles that float on water concentrate in either the nodes or antinodes of a standing wave, depending on whether they are hydrophilic or hydrophobic, as a result of a surface tension effect (Falkovich et al., 2005).

### 6.3 RISE AND FALL OF WATER IN SOIL PORES

Water is attracted into soil pores predominantly because of the attraction of water to other surfaces (adhesion) and because of capillarity. Surface tension controls the rise or fall of a liquid in a capillary tube. We have discussed surface tension and the equation to determine the height of rise in capillary tubes. We now discuss the rise and fall of water in soil pores (capillary tubes) and how the rise and fall determine the soil moisture characteristic curve. We follow the analysis of Kirkham (1961, pp. 24–29).

If one keeps track of the moisture withdrawn from an initially saturated soil core as greater tension is successively applied, and then plots on the  $x$ -axis (abscissa) water content (moisture percent by volume in the soil, not the water sucked out) and on the  $y$ -axis (ordinate), tension head

(positive units) or matric potential (negative units), the curve so obtained will be the so-called *moisture characteristic* or the *soil water characteristic curve* (ABCD in Figure 6.8). The curve also is called the *water retention curve* or the *water release curve* (Soil Science Society of America, 2008). The moisture percentage on such a curve may be based on oven-dry weight, but in drainage work, as in the figure, the soil moisture characteristic is most useful when the moisture is expressed on a volume basis because then the surface centimeters (depth) of irrigation water needed to replenish moisture in the sample is obtained from the characteristic. For example, a moisture percentage of 30% by volume at saturation means that, for a 10 cm dry soil layer, 3 cm of water must be applied to the surface to bring the 10 cm to saturation.

In Figure 6.8, one may think of the tension as being produced by a falling water table. One may verify the following on the figure: initially (point A), the bulk volume of the soil has all of its pore space, that is, 50% of its bulk volume, filled with water. For a 20 cm depth of water table, the moisture percentage at the soil surface is 40%; for a 40 cm depth of water table, 15%; and for a 100 cm depth, 8%. In Figure 6.8, if the water table had fallen to a 40 cm depth and then risen slowly to the soil surface, the moisture percentages would be those corresponding to the dashed line. The failure of the curve to retrace itself in the reverse direction is called *hysteresis*. In Figure 6.8, the soil moisture characteristic ABCD is that of a loam; for finer textured soils, the curves would be higher. If, for Figure 6.8,

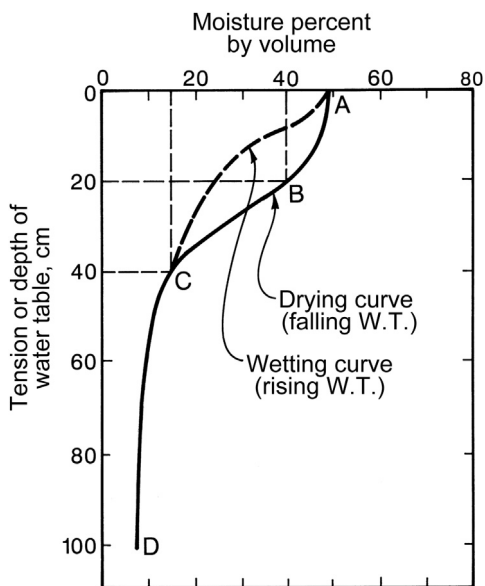


FIGURE 6.8 A soil moisture characteristic curve for a loam soil. From Kirkham (1961).

the water table for the dashed curve had not risen slowly, the moisture percentage for zero depth of the water table would be, because of trapped air, <50%. Even if the water table rises slowly, there is usually a small amount of trapped air, and, when hysteresis loops are determined experimentally, they are not seen to return to the original point.

We pause here to say a few words about hysteresis. It comes from the Greek *hysteresis*, a coming short or deficiency. It is a word used in physics and its definition is “a lag in the effect in a body when the force acting on it is changed; especially, a lag in the change of a magnetization behind the varying magnetizing force” ([Webster’s New World Dictionary of the American Language, 1959](#)). Because hysteresis relates to a physical system, a hysteretic curve can be repeated (e.g., the curves in [Figure 6.8](#) for a loam soil). Its use to describe a biological system should be approached with caution. For example, curves relating leaf water potential to evapotranspiration have been called *hysteretic* ([Sharratt et al., 1983](#)), but such curves are not repeatable and depend on physiological factors such as stomatal closure.

If the soil is saturated to the surface and covered by a thin layer of water, there will be no tension in the soil pores (voids). If the water table falls through the soil surface, tension will develop in the soil pores. If the pores are of the same diameter, they will start to drain and the water level in them will fall the same distance the water table falls. The maximum tension that the falling water table can exert on a soil pore at the soil surface is  $\rho_w g h$  dyne/cm<sup>2</sup>, where  $h$  is the depth of the water table below the soil surface. If the diameter of the pore is too large to support this tension, the pore will not be subject to the maximum tension.

However, pores in the soil are not all the same diameter. [Figure 6.9](#) illustrates what happens in a soil pore of variable diameter when the water table falls for six different cases of water table fall. The depth of soil and the length of the pore channel for each case are taken as 15 cm, so that for the heights of capillary rise shown, the diameter of tube nearest the surface is calculated to be 0.075. Thus the scale in the horizontal direction is, as seen in the figure ( $2/0.075 =$ ), 27-fold that of the vertical direction. In part A of the figure, the soil is shown saturated to the surface. In parts B, C, D, E, and F, the water table is shown at successively greater depths. In parts B and C, a 4 cm height of water column is held. In part D, only sufficient water curvature has developed in the narrow neck to support about 5 cm height of water. In part E, additional curvature has developed in the narrow neck, such that about 8 cm height of water is supported. In part E, the water table is at 13 cm depth, and in part F, it is at 15 cm depth, a drop of 2 cm. In dropping these 2 cm, the ability of the narrow neck to support the needed 2 cm is exceeded and the pore then empties suddenly and discontinuously to about the level of the water table. This example shows that the emptying of individual pores occurs discontinuously. When the water is removed from a large number of pores, as for any soil

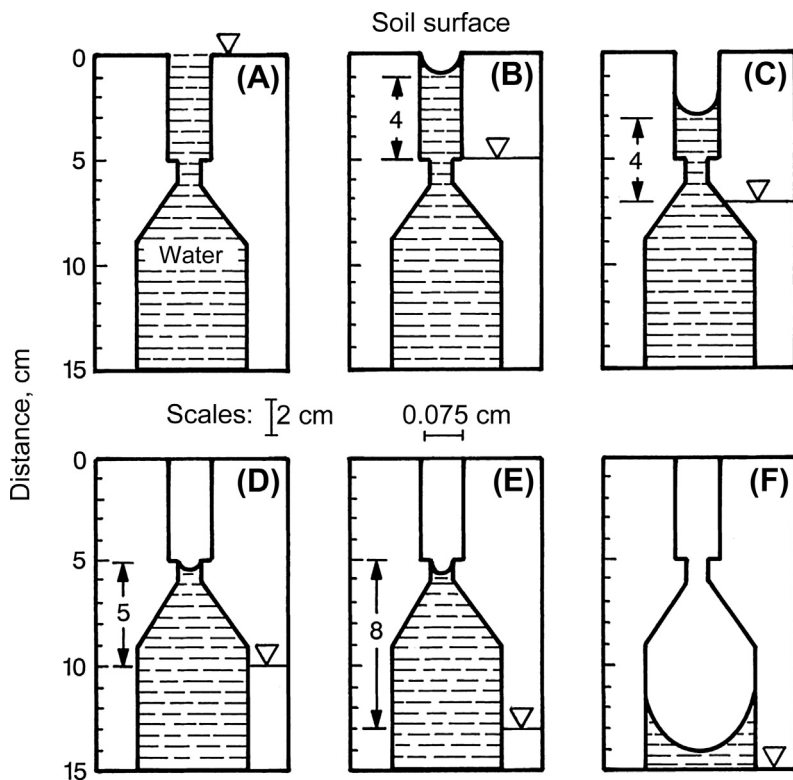


FIGURE 6.9 The falling water table in a soil pore (channel) of variable diameter. Note the difference in the vertical and horizontal scales. The water table is indicated by the inverted Greek “delta”. From Kirkham (1961).

sample, a graph of moisture percentage versus tension (or matric potential) does not show the discontinuous nature of the pore-emptying process. The example also shows that soil pores can be filled with water (saturated), yet the water is under tension in the pores.

In Figure 6.10, at the left, three shapes of pores are shown when the water table has fallen from level A to level B. The same three pores are shown at the right when the water table has risen from level C (say) to level B. At the left, the pores are filled up to the height  $h_c$ , the capillary height of rise. At the right, only one pore is filled up to the height  $h_c$ ; one pore is empty; and one is partially filled. The soil at the left, for the water table falling, has a much higher moisture percentage than the soil at the right, for the water table rising.

Figure 6.10 also gives a physical picture for hysteresis shown in Figure 6.8. A soil that is being wetted up from a rising water table holds less water than a soil that is being dried down. For the falling water table, water is held in tubes of supercapillary size if there is a restriction of

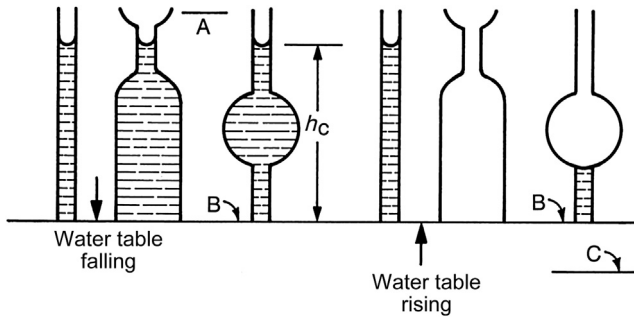


FIGURE 6.10 Soil pore conditions for a falling and for a rising water table. From [Kirkham \(1961\)](#).

capillary size at or below the height of capillary lift. Water can be drawn up above a water table, however, only by a continuous capillary opening without supercapillary enlargements. Hence, more water is held in the *capillary fringe*, which is the thickness of saturated water held by capillarity above the water table, above a sinking water table than above a rising water table. These concepts were explained by [Tolman \(1937\)](#) of Stanford University in his classic book, *Ground Water*.

It is apparent from [Figure 6.10](#) that applications of subirrigation water to raise the water table will not result in the same amount of moisture in the capillary fringe as will applications of surface water. Subirrigation would provide more soil aeration than surface addition of water. This may be desirable in some cases.

## 6.4 APPENDIX: BIOGRAPHY OF MARQUIS DE LAPLACE

Pierre Simon Laplace (1749–1827), the great French mathematician and astronomer, was born at Beaumont-en-Auge in Normandy on March 28, 1749, where his father owned a small estate. At the age of 16, he went to the University of Caen, where his mathematical genius was soon recognized. In 1767, he went to Paris and was appointed professor at the École Militaire. Shortly afterward Laplace discovered that any determinant is equal to the sum of all its minors that can be formed from any selected set of its rows, each minor being multiplied by its algebraic supplement. This theorem has been described as the most important in the subject and has been named after him ([Whitrow, 1971](#)).

Laplace next turned his attention to celestial mechanics. In 1773, he took up one of the outstanding problems that until then had resisted all attempts at solution in terms of Newtonian gravitation: the problem of why Jupiter's orbit appeared to be continually shrinking while Saturn's was continually expanding ([Whitrow, 1971](#)). In a memoir published in

three parts (Academy of Science, 1784–1786), Laplace showed that this phenomenon has a period of 929 years. The phenomenon arises because the mean motions of the two planets are nearly commensurable. The main object of this memoir, however, was to establish the permanence of the solar system for all time. The mutual gravitation interactions of the component bodies of the solar system were so many and varied that Newton had come to the conclusion that divine intervention was required from time to time if the system were to be preserved in anything like its present state. Despite increasing knowledge of planetary perturbations, no advance beyond this position was made until Laplace finally succeeded in showing that, because all planets revolve around the sun in the same direction, the eccentricities and inclinations of their orbits to each other will always remain small, provided they are small at a particular epoch, as in fact they are at present.

Laplace's monumental *Mécanique céleste* appeared in five volumes between 1799 and 1825. It summarized the work of three generations of mathematicians on gravitation. In a supplement to the fourth volume of his treatise on celestial mechanics, Laplace furthered our understanding of capillary phenomena. There he considered free surfaces, including equilibrium shapes of free menisci (Pomeau and Villermaux, 2006). In 1796, he published *Exposition du système du monde*, a semipopular book which is a model of French prose. In a celebrated memoir on the gravitational fields of spheroids, published in 1785, he introduced the potential function and the equation named after him. Laplace is also famous for his *Théorie analytique des probabilités* published in 1812 and his *Essai philosophique* on the same subject published in 1814. The former introduced important new ideas in pure mathematics, in particular, the theory of Laplace transforms (Whitrow, 1971).

In 1799, when Napoleon I became first consul, he appointed Laplace minister of the interior, but dismissed him after 6 weeks for bringing "the spirit of infinitesimals into administration" and elevated him to the senate. Later, Laplace was made a count of the empire, and after the restoration of the Bourbons he was designated a marquis. He died in Paris on March 5, 1827 (Whitrow, 1971).

## References

- Aly, Saleh M., Letey, J., 1988. Polymer and water quality effects on flocculation of montmorillonite. *Soil Sci. Soc. Am. J.* 52, 1453–1458.
- Bartlett, John, 1955. Bartlett's Familiar Quotations. Thirteenth and Centennial ed. Little, Brown and Company, Boston.
- Buderi, R., 1996. *The Weapon that Won the War*. Simon Schuster, Little, Brown, New York.
- Cattell, J., 1955. In: *American Men of Science. A Biographical Directory*. vol. 1. Physical Sciences, ninth ed. Science Press, Lancaster, Pennsylvania; and R.K. Bowker, New York, New York, p. 1164.

- Cattell, J., 1961. In: *American Men of Science. A Biographical Directory. The Physical and Biological Sciences*, Tenth ed. Jaques Cattell Press, Tempe, Arizona, p. 2437.
- De Boodt, M., 1975. Use of soil conditioners around the world. In: Gardner, W.R., Clapp, C.E., Gardner, W.H., Moldenhauer, W.C., Mortland, M.M., Rich, C.I. (Eds.), *Soil Conditioners. SSSA Special Publication No. 7. Soil Science Society of America, Madison, Wisconsin*, pp. 1–12.
- Dickinson, M., 2003. How to walk on water. *Nature* 424, 621–622.
- Falkovich, G., Weinberg, A., Denissenko, P., Lukashuk, S., 2005. Floater clustering in a standing wave. *Nature* 435, 1045 (one page only).
- Gao, X., Jiang, L., 2004. Water-repellent legs of water striders. *Nature* 432, 36 (one page only).
- Hu, D.L., Chan, B., Bush, J.W.M., 2003. The hydrodynamics of water strider locomotion. *Nature* 424, 663–666.
- Kirkham, D., 1961. *Lectures on Agricultural Drainage*. Institute of Land Reclamation, College of Agriculture, Alexandria University, Alexandria, Egypt (Copy in the Iowa State University Library, Ames, Iowa.).
- Kirkham, D., Powers, W.L., 1972. *Advanced Soil Physics*. Wiley-Interscience, New York.
- Kirkham, D., Runkles, J., 1952. Evaluation of new soil conditioners. *Trans. [Iowa] State Hort. Soc.* 37, 41–46.
- Lentz, R.D., Sojka, R.E., 2009. Long-term polyacrylamide formulation effects on soil erosion, water infiltration, and yields of furrow-irrigated crops. *Agron. J* 101, 305–314.
- Linford, L.B., 1930. Soil moisture phenomena in a saturated soil. *Soil Sci.* 29, 227–235.
- Liu, X., Duncan, J.H., 2003. The effects of surfactants on spilling breaking waves. *Nature* 421, 520–523.
- Mertens, J., 2006. Oil on troubled waters: Benjamin Franklin and the honor of Dutch seamen. *Phys. Today* 59 (1), 36–41.
- Pomeau, Y., Villermanx, E., 2006. Two hundred years of capillarity research. *Phys. Today* 59 (3), 39–44. + cover.
- Porter, A.W., 1971. Surface tension. *Encyclopaedia Britannica* 21, 442–450.
- Schamp, N., Huylebroeck, J., Sadones, M., 1975. Adhesion and adsorption phenomena in soil conditioning. In: Gardner, W.R., Clapp, C.E., Gardner, W.H., Moldenhauer, W.C., Mortland, M.M., Rich, C.I. (Eds.), *Soil Conditioners. SSSA Special Publication No. 7. Soil Science Society of America, Madison, Wisconsin*, pp. 13–23.
- Schaum, D., 1961. *Theory and Problems of College Physics*. Schaum Publishing, New York.
- Seitz, F., 1996. How Allies Shared Radar Secrets. Book Review of the *Weapon that Won the War* by Robert Buder. Simon and Schuster, Little, Brown. *Nature* 384, 424–425.
- Sharratt, B.S., Reicosky, D.C., Idso, S.B., Baker, D.G., 1983. Relationships between leaf water potential, canopy temperature, and evapotranspiration in irrigated and nonirrigated alfalfa. *Agron. J.* 75, 891–894.
- Soil Science Society of America, 2008. *Glossary of Soil Science Terms 2008*. Soil Science Society of America, Madison, Wisconsin.
- Sojka, R.E., Lentz, R.D., Westermann, D.T., 1998. Water and erosion management with multiple applications of polyacrylamide in furrow irrigation. *Soil Sci. Soc. Am. J.* 62, 1672–1680. + cover.
- Sophocleous, M.A., 2010. Understanding and explaining surface tension and capillarity: an introduction to fundamental physics for water professionals. *Hydrogeol. J.* 18, 811–821.
- Tolman, C.F., 1937. *Ground Water*. McGraw-Hill, New York.
- Wallace, A., Terry, R.E. (Eds.), 1998. *Handbook of Soil Conditioners*. Marcel Dekker, New York.
- Whitrow, G.J., 1971. Laplace, Pierre Simon. *Encyclopaedia Britannica* 13, 716–717.
- Webster's New World Dictionary of the American Language, college ed., 1959. World Publishing, Cleveland.