CHAPTER

7

Water Movement in Saturated Soil

Understanding movement of water in saturated soil is important in drainage and groundwater studies. The French hydraulic engineer, Henry Darcy (1803–1858) experimentally determined the law that governs the flow of water through saturated soil (1856), which is called Darcy's law. (See the Appendix, Section 7.7, for a biography of Darcy.)

7.1 DARCY'S LAW

To illustrate Darcy's law, let us consider Figure 7.1, which shows water flowing through a soil column of length L and cross-sectional area, A (Kirkham and Powers, 1972, p. 47). The law can be stated as follows:

$$Q = -KA(h_2 - h_1)/(z_2 - z_1), \tag{7.1}$$

where Q is the quantity of water per second such as in cubic centimeters per second, often called the "flux"; K, centimeters per second, is the

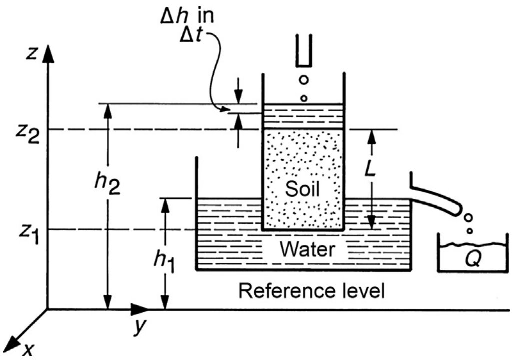

FIGURE 7.1 Illustration of Darcy's law. *From Kirkham and Powers (1972), p. 47, ©1972. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.*

http://dx.doi.org/10.1016/B978-0-12-420022-7.00007-0

"hydraulic conductivity" (the law defines K); heads h_1 and h_2 and distances z_1 and z_2 are as shown in Figure 7.1. The reference level here is the x, y plane. The head h_1 is the hydraulic head for all points at the bottom of the soil column, that is, at $z = z_1$, and similarly, the head h_2 applies to all points at the top of the soil column, $z = z_2$. The length of the column is $z_2 - z_1 = L$. The negative sign in the Darcy equation is used so that a positive value of Q will indicate a flow in the positive z direction. The positive z direction is measured from z_1 to z_2 (Kirkham and Powers, 1972, pp. 46–47).

In the Darcy law equation, the quantity $(h_2 - h_1)/(z_2 - z_1)$ is called the "hydraulic gradient" i; the ratio Q/A is called the "flux per unit cross-section" or "flux density" (cubic centimeters per second) divided by centimeters squared. The ratio Q/A is also called the "Darcy velocity" v or, very often, just the velocity v. Therefore, Darcy's law may be written as $v = -Ki$. The "actual velocity" of the water in the soil is much greater than the Darcy velocity. The actual velocity is on the average v/f where f is the "porosity" (Kirkham and Powers, 1972, p. 47). The porosity is the volume of pores in a soil sample divided by the bulk volume of the sample (Soil Science Society of America, 2008). The pores can be filled with air or water. (Because Darcy's law is for saturated soil, the pores are filled with water when it applies). The percent porosity in the soil can be determined from the following equation (Millar et al., 1965, p. 54):

$$\% \text{ porosity} = [1 - (\text{bulk density}/\text{particle density})] \times 100. \tag{7.2}$$

The Darcy velocity v means more than flux per unit area, Q/A. In Figure 7.1, suppose that the supply of water shown dripping into the soil column is abruptly cut off during a short time interval Δt during which h_2 decreases by Δh. Let Δq be the volume of water flowing downward through the soil in Δt. Because Q is the flow per second, we may write Δq as $\Delta q = Q\Delta t$, and we also have by continuity of flow $\Delta q = A\Delta h$. Therefore, $Q\Delta t = A\Delta h$, and $Q/A = \Delta h/\Delta t$. Physically, $\Delta h/\Delta t$ is a velocity; therefore, so is $v = Q/A$. Thus, the Darcy velocity v represents the rate $\Delta h/\Delta t$ approaches $\mathrm{d}h/\mathrm{d}t$ of fall of surface water in Figure 7.1. If the hydraulic gradient is unity (pressure potential is the same at the top and bottom of the soil column), then $v = -K$. Thus, it is determined that K is numerically equal to the rate of fall of a thin layer of ponded water into the soil, under only the force of the earth's gravitational pull. We also see that K is the velocity under a unit hydraulic gradient (Kirkham and Powers, 1972, p. 48).

Flow in a vertical soil column has been used to derive and illustrate Darcy's law. However, the law and principles developed in the preceding paragraphs apply for the flow of water in any direction in the soil.

For a discussion of the use of Darcy's law in groundwater hydrology, see Anderson (2007).

7.2 HYDRAULIC CONDUCTIVITY

The hydraulic conductivity should not be confused with the "intrinsic permeability", sometimes just called the "permeability", of the flow medium. The intrinsic permeability, symbolized by k by M. Muskat (1946) in his classic treatise (Muskat was a petroleum engineer in the United States well known for his studies in the 1930s and 1940s of fluid flow through porous media), is equal to $K\eta/\rho g$, where K is the Darcy hydraulic conductivity, η is the fluid viscosity, ρ is the fluid density, and g is the acceleration due to gravity. Dimensionally, k is an area (L^2). The units of K are meters per day, which is the same as (cubic meters per square meter)/day. That is, K may be interpreted as the cubic meter of water seeping through a square meter of soil per day under a unit hydraulic gradient (Kirkham and Powers, 1972, pp. 48–49).

Hydraulic conductivity in natural field soil is governed by factors such as cracks, root holes, worm holes, and stability of soil crumbs. Texture, that is, the percent of the primary particles of sand, silt, and clay, usually has a minor effect on hydraulic conductivity, except for disturbed soil materials. The hydraulic conductivity of natural soils in place varies from about 30 m/day for a silty clay loam to 0.05 m/day for a clay (Kirkham, 1961a, p. 46; Kirkham, 1961b). The hydraulic conductivity for disturbed soil materials varies from about 600 m/day for gravel to 0.02 m/day for silt and clay. The value of K can be made higher or lower by soil management. Roots of crops after decay increase K; compaction of soil by animals or machinery decreases K, at least in the surface soil.

Ordinarily one considers K in $v = -Ki$ to be a constant under saturated flow. It is a constant if (1) the physical condition of the soil and of the water does not change in space or time as the water moves through the soil (e.g., the soil is "isotropic", i.e., hydraulic conductivity is the same regardless of the direction of measurement) and if (2) the type of flow is laminar, that is, not turbulent. In laminar flow, two particles of water seeping through the soil will describe paths (streamlines) that never cross each other. In turbulent flow, eddies and whirls develop. The possibility of turbulent flow is considered in soil only if the soil is a coarse sand or gravel, and then only if the hydraulic gradients are large (larger than those found in most problems of interest to agricultural soil scientists).

7.3 LAPLACE'S EQUATION

To solve groundwater seepage and drainage problems, it is desirable to have a general differential equation (Kirkham and Powers, 1972, p. 49), and Laplace's equation, which is a familiar equation occurring in nearly all branches of applied mathematics, applies. Laplace's equation is derived from Darcy's law and the *equation of continuity.* (See the appendix of Chapter 6 for a biography of Laplace.) The equation of continuity states mathematically that mass can neither be created nor destroyed. We can state the equation of continuity in words, as follows: For a volume element x times y times z, the change in the velocity of water in the x direction plus a change in velocity of water in the y direction plus a change in the velocity of water in the z direction are equal to the total change in water content, θ, per unit time of the volume element under consideration. That is, the inflow of water in the element minus outflow of water is equal to the water accumulated. Let us imagine a rectangular x, y, z system of coordinates that is established in a homogeneous porous medium of constant hydraulic conductivity, and let h be the hydraulic head referred to an arbitrary reference level for a point (x, y, z) and let time be t and v_x, v_y, and v_z be the velocity of water flowing in the x, y, and z directions, respectively; then, with θ being the volume of water per unit volume of bulk soil, from the equation of continuity,

$$-\left[(\partial v_x/\partial_x) + \left(\partial v_y/\partial_y\right) + (\partial v_z/\partial_z)\right] = \partial\theta/\partial t \tag{7.3}$$

and from Darcy's law, one may, for an incompressible steady-state flow in a porous medium where K is constant, derive the expression (Kirkham and Powers, 1972, p. 52)

$$\left(\partial^2 h/\partial x^2\right) + \left(\partial^2 h/\partial y^2\right) + \left(\partial^2 h/\partial z^2\right) = 0, \tag{7.4}$$

as the expression governing groundwater flow. The equation is abbreviated $\nabla^2 h = 0$.

Charles S. Slichter (1899), a mathematician at the University of Wisconsin, was the first to show in 1899 that Laplace's equation applies to the motion of groundwater (Kirkham and Powers, 1972, p. 52). Many mathematical solutions for groundwater flow using Laplace's equation have been done by Don Kirkham (1908−1998) of Iowa State University.

7.4 ELLIPSE EQUATION

In addition to Darcy's equation and Laplace's equation, another important equation for saturated flow is called the Colding equation after the Danish engineer A. Colding, who published it in 1872 (van der Ploeg et al., 1997). It is used to determine drain spacings. The equation is also called the ellipse equation, because it describes an ellipse. Therefore, before we look at the Colding equation, let us study an ellipse.

The locus of a point P that moves in a plane so that the sum of its distances from two fixed points in the plane is constant is called an

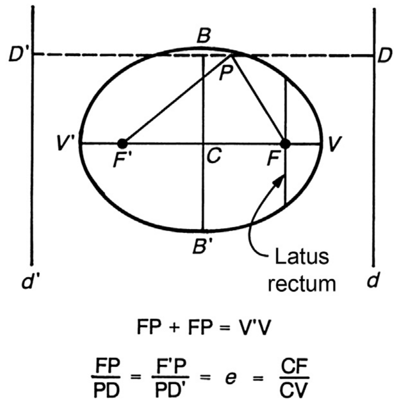

FIGURE 7.2 The ellipse. It is the locus of a point P that moves in a plane so that the sum of its distances from two fixed points in the plane, F and F', is constant. *From Ayers (1958), p. 322, ©1958. This material is reproduced with permission of The McGraw-Hill Companies.*

"ellipse" (Ayers, 1958, p. 322). The fixed points F and F' are called the "foci", and their midpoint C is called the "center" of the ellipse (Figure 7.2). The line FF' joining the foci intersects the ellipse in the points V and V', called the "vertices". The segment $V'V$ intercepted on the line FF' by the ellipse is called its "major axis"; the segment $B'B$ intercepted on the line through C perpendicular to $F'F$ is called its "minor axis".

A line segment in which the extremities are any two points on the ellipse is called a "chord". A chord that passes through a focus is called a "focal chord"; a focal chord perpendicular to the major axis is called a "latus rectum".

The equation of an ellipse assumes its simplest ("reduced") form when its center is at the origin and its major axis lies along one of the coordinate axes. When the center is at the origin and the major axis lies along the x-axis, the equation of the ellipse is (Figure 7.3)

$$\left(x^2/a^2\right) + \left(y^2/b^2\right) = 1. \tag{7.5}$$

Figure 7.3 is an oblate ellipse. "Oblate" comes from the Latin "oblatus", which means "offered" or "thrust forward", and means "being thrust forward at the equator". In geometry, oblate means flattened at the poles.

When the center is at the origin and the major axis lies along the y-axis, the equation of the ellipse is (Figure 7.4)

$$\left(x^2/b^2\right) + \left(y^2/a^2\right) = 1. \tag{7.6}$$

Figure 7.4 is a prolate ellipse. "Prolate" comes from the Latin "prolatus", which is the past participle of "proferre", "to bring forward". Prolate means "extended or elongated at the poles".

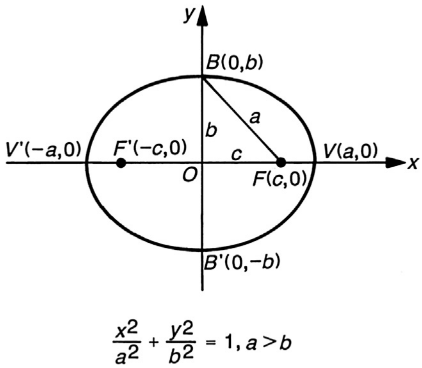

FIGURE 7.3 An oblate ellipse. *From Ayers (1958), p. 323, ©1958. This material reproduced with permission of The McGraw-Hill Companies.*

A circle is a special form of an ellipse in which the semimajor and semiminor axes are equal in length. The equation of a circle is

$$x^2 + y^2 = r^2, \tag{7.7}$$

where r is the radius of the circle, and the circle has its center at the origin of the x, y coordinate system.

If we are dealing in three dimensions, we have an "ellipsoid". The locus of the equation

$$x^2/a^2 + y^2/b^2 + z^2/c^2 = 1 \tag{7.8}$$

is called an ellipsoid (Figure 7.5). If at least two of a, b, c are equal, the locus is called an ellipsoid of revolution, and if $a = b = c$, the locus is a sphere (Ayers, 1958, p. 387).

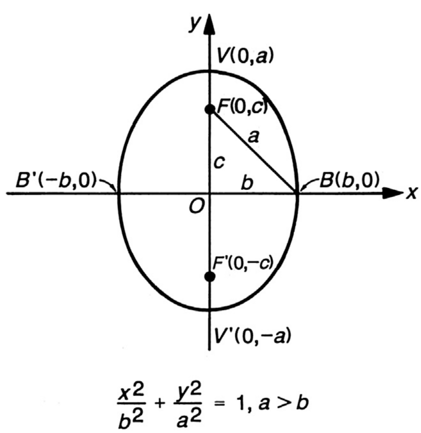

FIGURE 7.4 A prolate ellipse. *From Ayers (1958), p. 323, ©1958. This material reproduced with permission of The McGraw-Hill Companies.*

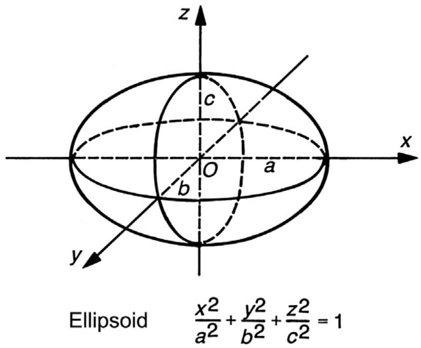

FIGURE 7.5 The ellipsoid. *From Ayers (1958), p. 387, ©1958. This material is reproduced with permission of The McGraw-Hill Companies.*

The need for soil drainage is widespread around the world, not only in the wet soils of northern Europe and in the states of the United States that are wet in the spring (e.g., Iowa) but also in irrigated regions. It is generally accepted that the Danish engineer Colding was the first to derive a drain-spacing equation based on modern soil—water flow concepts. For parallel, equally spaced tile (tube) drains resting on an impermeable barrier, and for steady-state flow conditions, Colding (1872) derived the following expression (van der Ploeg et al., 1997, 1999):

$$L^2 = [(4K)/R]b^2, \tag{7.9}$$

where L is the drain distance, K is the soil hydraulic conductivity, R is the constant rate of precipitation, and b is the maximum height of the water table above the drain level, midway between the drains (Figure 7.6). Equation (7.9) describes an ellipse, with the drain distance L being the

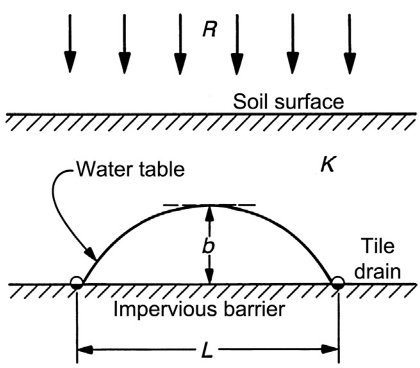

FIGURE 7.6 Schematic representation of the subsurface drain problem, as considered by Colding. *From van der Ploeg et al. (1999), ©1999, Madison, Wisconsin. Reprinted by permission of the Soil Science Society of America.*

major axis and the maximum water table height b above the drain level being the semiminor axis (Kirkham and Powers, 1972, pp. 90, 92).

It is not known if Colding was familiar with the work of Darcy (1856), but apparently he was not, because he does not mention him in his work. Darcy's work on hydraulic conductivity did not receive much attention until the second edition of the book by Dupuit (1863), and even then it took time for people to become familiar with it. Nevertheless, Colding was using Darcy-like theory to derive his equation.

The US Bureau of Reclamation uses the Colding equation, as modified by Hooghoudt (1940) for design purposes (van der Ploeg et al., 1999). Instead of equally spaced tile drains, (Hooghoudt 1937, 1940) considered equally spaced drainage ditches overlying an impervious layer (Figure 7.7). (For a biography of Hooghoudt, see Raats and van der Ploeg, 2005.) In the Imperial Valley in California, the Colding equation, as modified by Aronovici and Donnan (1946) is used (van der Ploeg et al., 1999). Aronovici and Donnan, apparently unaware of the work of Hooghoudt, also developed a modified Colding equation almost identical to the Hooghoudt (1940) equation. It is important to recognize that some of today's most common drainage design practices are based on the Colding (ellipse) equation.

The ellipse is an important geometric form because of its widespread application in soil–water relations and other aspects of nature. Apollonian curves—that is, ellipses, parabolas, and hyperbolas—all have amazing relationships hidden in them (Anvar Kacimov, personal communication, December 9, 1999). (See the Appendix, Section 7.6, for a biography of Apollonius, a Greek geometer.) Johannes Kepler (1571–1639, German astronomer and mathematician) also came to his celestial mechanics formula from the geometric side. (See the appendix of Chapter 30 for a biography of Kepler.) He first selected an ellipse and then applied it to orbits (Goodstein and Goodstein, 1996). To understand the

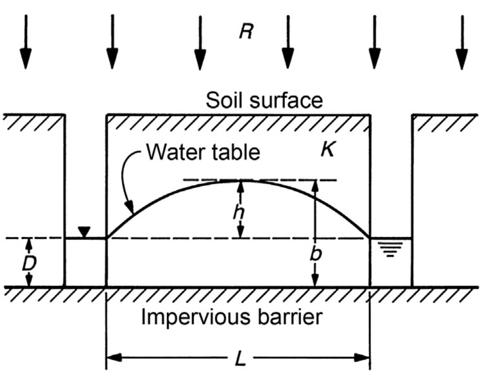

FIGURE 7.7 Geometric representation of a homogeneous soil, underlain by an impervious barrier, which is drained by parallel, equally spaced ditches, where the ditches reach the impervious barrier, as considered by Hooghoudt. *From van der Ploeg et al. (1999), Madison, Wisconsin. Reprinted by permission of the Soil Science Society of America.*

interception of solar radiation by plant leaves, which we discuss in Chapter 30, we need to study Kepler's laws of planetary motion. He saw that the planets orbit the sun in elliptical paths.

Other examples of Apollonian curves used in soil–water studies include the work by Kacimov (2000), who used the special case of an ellipsoid, the hemisphere, to study three-dimensional groundwater flow to a lake, and the work by Kirkham and Clothier (1994), who used the ellipsoidal equation (Eqn (7.8)) to describe the shape of the wet front as it expands under a surface disc that is infiltrating water into the soil.

7.5 LINEAR FLOW LAWS

Darcy's law is a linear flow law. It is linear because the v, the Darcy velocity, of $v = -Ki$, varies linearly with the hydraulic gradient i (Kirkham and Powers, 1972, p. 74). Ohm's law is one of the most common linear flow laws and is used in problems concerning the flow of electricity. In Ohm's law, the current transported is linearly related to the difference in the driving potential across the system. We shall return to Ohm's law when we study electrical analogues (Chapter 22). Gauss's law, used in studying electrostatic fields, is another linear flow law (Kirkham, 1961a, p. 104). Poiseuille's law for flow of a liquid through a capillary tube is not a linear flow law, because an exponent >1 occurs in it. Poiseuille found that the volume of fluid moving in unit time along a cylinder is proportional to the fourth power of its radius. We will use Poiseuille's law to study flow of water in the vessel members in the xylem tissue (Chapter 15).

Table 7.1 shows that linear flow laws are similar. For example, Darcy's law is similar to Ohm's law, Fick's law, and Fourier's law. These laws are commonly used in soil physics; Darcy's law is used in studies of water flow, Fick's law in studies of gaseous flow (Kirkham, 1994), and Fourier's law in studies of heat flow. It is important to know the similarities, because, for water flow (Darcy's law) problems for which solutions are desired, there may exist analogous electrical flow (Ohm's law) or heat flow (Fourier's law) problems that have been already solved. These solutions can be used for writing down directly the solution of the desired water flow problem (Kirkham, 1961a, p. 104).

Linear flow phenomena are involved in other studies, as well, as listed by Moon and Spencer (1961):

1. *High-voltage engineering:* Design of high-tension transformer bushings, transmission-line insulators, electrostatic voltmeters, and Van de Graaf generators
2. *Magnetostatics:* Calculations for generators, motors, lifting magnets, solenoids, synchrotrons

TABLE 7.1 Linear Flow Laws Encountered in Soil—Plant—Water Relationships. No Exponents (Other Than 1) Appear in a Linear Flow Law

Linear Flow Laws

Law	Quantity Transported per sec Across Flow Region	Transport Coefficient of Flow Region	Difference in Driving Potential Across System	Form Factor F for System (e.g., Rectangular Box)[†]
Ohm $I = \frac{\sigma \Delta V A}{L} = \frac{V}{R}$[‡]	$I =$ Amperes or coulombs per sec	$\sigma =$ Specific electrical conductivity (S/cm)	$\Delta V =$ Difference in electrical potential between input and output (V)	$F = \frac{A}{L}$
Darcy $Q = \frac{k \Delta h A}{L}$	$Q = \mathrm{cm}^3/\mathrm{sec}$	$k =$ Hydraulic conductivity (cm/sec)	$\Delta h =$ Difference in head of water column between input and output (cm)	$F = \frac{A}{L}$
Fick $Q = \frac{D \Delta C A}{L}$	$Q = \mathrm{g}/\mathrm{sec}$	$D =$ Diffusion coefficient ($\mathrm{cm}^2/\mathrm{sec}$)	$\Delta C =$ Difference in concentration of gas at input and output (g/cm^3)	$F = \frac{A}{L}$
Fourier $Q = \frac{K \Delta T A}{L}$	$Q = \mathrm{cal}/\mathrm{sec}$	$K =$ Thermal conductivity (cal per sec per cm^2 for a thickness of 1 cm and temperature difference of 1 °C)	$\Delta T =$ Difference in temperature between input and output (°C)	$F = \frac{A}{L}$

[†]A = *Cross-sectional area of the system (box) perpendicular to the direction of flow;* L = *length of the system (box) through which the flow occurs. The form factor is for two-dimensional flow problems; it is the same for equal geometries of the flow region.*

[‡]R *in this equation = resistance in ohms, Ω. (1* S = *1/Ω = mho).*

3. *Heat conduction:* Determination of temperature distributions in electric machinery, heating devices, cable ducts, and refrigerators
4. *Fluid flow:* Calculation of flow about airfoils and other obstructions, seepage of fluids through sand
5. *Electrodynamics:* Determination of resistance of irregular-shaped conductors, electrical prospecting
6. *Electrostatics:* Design of vacuum tubes, electron microscopes, and cathode ray oscilloscopes, television tubes
7. Elasticity: Vibration engineering, structural engineering
8. *Diffusion:* Calculation of the heating and cooling of ingots, the annealing of glass, and the diffusion of fluids
9. *Acoustic waves:* Design of loud speakers and microphones
10. *Electromagnetic waves:* Calculation of wave guides and antennas

To the list of Moon and Spencer (1961) can be added an 11th item:

11. *Mass flow of gas under a small pressure gradient*

7.6 APPENDIX: BIOGRAPHY OF APOLLONIUS OF PERGA

Apollonius of Perga (Pergaeus), a Greek geometer of the Alexandrian school, was probably born about 25 years later than Archimedes (i.e., ~261 BC). He flourished in the reigns of Ptolemy Euergetes and Ptolemy Philopator (247–205 BC) (Heath and Neugebauer, 1971). His treatise on *Conics* gained him the title of the Great Geometer, and, through this work, his fame has been transmitted to modern times. Most of his other treatises were lost, although their titles and a general indication of their contents were passed on by later writers, especially Pappus. After Apollonius wrote the *Conics* in eight books in a first edition, he brought out a second edition, considerably revised with regard to books I and II.

The degree of originality of the *Conics* can best be judged from Apollonius's own prefaces. He made the fullest use of his predecessors' works, such as Euclid's four books on conics, which is clear from his allusions to Euclid, Conon, and Nicoteles. Books I–IV form an "elementary introduction" (i.e., contain the essential principles) and the rest of the books are specialized investigations. Apollonius introduced the names "parabola", "ellipse", and "hyperbola". Books V–VII are highly original. Apollonius's genius takes its highest form in book V, where he treats normals as minimum and maximum straight lines drawn from given points to the curve (independently of tangent properties), discusses how many normals can be drawn from particular points, finds their feet by construction, and gives propositions determining the center of curvature at any point (Heath and Neugebauer, 1971).

Six other treatises by Apollonius (each in two books) were concerned with cutting off a ratio, cutting off an area, determinate sections, tangencies, inclinations, and plane loci. An Arabic version of the first treatise was found toward the end of the seventeenth century in the Bodleian library by Edward Bernard, who began a translation of it. (The Bodleian library is a famous library at Oxford University in England named after Sir Thomas Bodley, 1545–1613, an English diplomat and man of letters and founder of the library.) Edmund Halley (1656–1742), the English astronomer, finished the translation and published it with a restoration of the second treatise (1706).

Other works by Apollonius referred to by ancient writers include (1) *On the Burning-Mirror*, where the focal properties of the parabola probably were discussed; (2) *On the Cylindrical Helix*; (3) a comparison of the dodecahedron and the icosahedron inscribed in the same sphere; (4) a work which included Apollonius's criticisms and suggestions for the improvement of Euclid's *Elements*; (5) a work in which he showed how to find closer limits for the value of π than the $3\,{}^{1}\!/_{7}$ and $3\,{}^{10}\!/_{71}$ of Archimedes; (6) an arithmetic work on a system of expressing large numbers and showing how to multiply such large numbers; and (7) extensions of the theory of irrationals expounded in Euclid.

7.7 APPENDIX: BIOGRAPHY OF HENRY DARCY

Henry Philibert Gaspard Darcy (1803–1858) is best known for his scientific work on pipe flow (Howland, 1971). He lived in Dijon, France, for most of his life, where he was inspector general of bridges and highways. His father, a town functionary, died when he was 14 years old (Philip, 1995). His determined mother named him the English "Henry" instead of the French "Henri", and ensured that both Henry and his brother Hugues received the best education possible. Henry won a scholarship to the Dijon Polytechnic and in 1826 graduated brilliantly as a civil engineer. He married Henriette Carey in 1828, but they never had any children (Ik-Jae Kim, Graduate Student, Department of Biological and Agricultural Engineering, Kansas State University, personal communication, September 15, 2004).

Working as an engineer, he devoted his life to providing the town of Dijon with pure water. The waters of cities then, including Dijon, were often inadequate, always in short supply, and dirty. Dijon had at its disposition only wells plus the water of the Ouche, and well waters were not protected from contamination. The town of Dijon was crossed by the ancient bed of a small stream, the Suzon, which was uncovered over almost all its length, with no part paved, and served over a length of 1300 m as the main sewer for wastes of every kind. It was never cleaned, and during hot weather, the town was poisoned by pestilential odors.

To clean up the water, Darcy substituted the method that became standard (Philip, 1995). In 1833, Darcy, on his own initiative, presented his plan to the municipal authorities. The Municipal Council adopted his recommendations, and the General Council of Bridges and Highways (Ponts et Chaussées) approved all parts of the proposed plan. He developed a network of underground conduits with underground reservoirs. On September 6, 1840, without any errors or mishaps, the beneficial waters reached the reservoir of the Porte Guillaume. By 1844, the whole network of underground conduits had been completed (Philip, 1995). Consequently, Dijon possessed from 1840 the benefits that Paris did not discover until 20 years later, and enjoyed an abundance of water. Other towns asked for Darcy's assistance, such as Brussels, which officially asked for his help in 1851 and 1852 and adopted the plan that he provided.

Darcy had given his native town the better part of his life. For this work of 12–15 years, he wished to receive no remuneration. He would not agree even to be reimbursed for his expenses. He accepted only a gold medal that commemorated his work.

In 1848, the revolution overthrew King Louis-Philippe and brought in the radical and short-lived Second Republic. Despite the facts that Darcy was apolitical and that he had given generously of his own money to set up workers' cooperatives, the Second Republic saw him as a dangerous and reactionary collaborator with the ancient regime. Darcy was stripped of his offices and banished from Dijon. In 1852, the Second Republic was succeeded by the Second Empire of Emperor Napoleon III, and Darcy was politically rehabilitated.

In 1854, Darcy was 51, but in poor health. Ever since his days as a young engineer, he had been a prey to nervous troubles and to attacks producing symptoms of meningitis. Time and overwork gradually made these attacks more acute. He suffered a bad period in 1845, while he was directing the works at Blaisy. Later, in Paris, he lost consciousness during a conference, and in 1853, he fell down in the open street. He took leave for several months, but, as he continued to suffer intolerably, he despaired and asked to be released from his responsibilities. Nevertheless, unable to stay inactive, he pursued his hydraulic experiments, and it was during these last years that he was able, thanks to financial help from the Ministry of Public Works, to carry out the work that he wrote up and published in 1856.

In 1857, the Académie des Sciences wished to elect him to the vacancy left by the mathematician Cauchy who had just died. (Baron Augustin Louis Cauchy, 1789–1857, was one of the greatest of modern French mathematicians.) Darcy was elected without discussion, but on January 2, 1858, he succumbed to pleurisy aggravated by angina and died in Paris.

Dijon gave him a public funeral appropriate to his great labors. The whole population went to receive his remains at the railway station, all the functionaries in uniform, armed soldiers lining the streets, the workers of cooperatives founded on his initiative carrying the coffin, and the bishop officiating. Sadly, 135 years after Darcy's death, when the whole town mourned it, nobody in Dijon knew who he was, even though his name appears in many places in Dijon (Philip, 1995).

There is in existence a collection of letters from Darcy to Henri Émile Bazin (1829–1917). Bazin was 26 years younger than Darcy, a hydraulic engineer working in Dijon whose researches on channel and pipe flow are well known. Bazin, acting as Darcy's assistant, was trained to be a careful and assiduous experimenter. He carried on Darcy's original program of tests on open-channel resistance. His studies also extended to wave propagation, to flow over weirs, and to the contraction of the liquid vein coming from an orifice. Bazin was elected to the French Academy of Sciences in 1865. He died on February 7, 1917, at Dijon (Howland, 1971).

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