PART ONE Theory

CHAPTER

1

Groundwater in Construction

The impact of groundwater on an underground construction project can be enormous. Water affects the design of the structure, the construction procedures, and the overall project cost. We have seen water problems of unexpected severity cause major delays, often requiring drastic re-designs. A high proportion of the claims and litigation in construction contracting arises from groundwater issues. There have been cases where entire projects were abandoned because of water, despite substantial investment in already completed construction. The concurrent trends of population growth and population concentration have sent land values soaring, creating a demand for the development of sites that were previously considered unsuitable; often groundwater, as it affects construction and long-term maintenance of a facility, must be addressed early in the planning stages.

There is need for professionalism in addressing groundwater concerns. We must understand the patterns of groundwater movement at the individual site and appreciate water's effect on the particular soils involved, for those are the two factors in the groundwater equation: how water moves in the soil and what water does to the soil. To the degree we understand these factors, our efforts to deal with groundwater will be more likely to succeed.

Fortunately, we have many more tools and methods today than once were available for the control of groundwater; the ways in which we analyze groundwater problems, and how we select and apply the available tools to solve them, have been much improved. Engineers and contractors confronted with groundwater problems can be much better equipped to solve them than were their predecessors of just a few years ago. Their chances of finding effective solutions will be enhanced if they are up to date in their understanding of groundwater phenomena, of the ways to identify and analyze site-specific situations, and the tools available to control them.

1.1 GROUNDWATER IN THE HYDROLOGIC CYCLE

The supply of water on the earth, although very large, is nonetheless finite. The bulk of this supply is in constant motion. Under the right conditions, water vapor condenses in the atmosphere and falls on the surface of the earth as precipitation in the form of rain or snow. Some of it becomes locked for long periods in the polar ice caps, although it remains in motion, creeping slowly in the glaciers toward a warmer climate where it melts. Of the precipitation falling in more temperate zones, some portion runs off directly from the land, forming surface streams in motion toward the sea. Another portion is absorbed into the ground. Of this infiltration, some portion never gets deeper than the upper soil horizon, the *zone of aeration*. Some of the water is re-evaporated directly to the atmosphere; some quantity is absorbed by plant roots and, in the process of contributing to the life cycle of the vegetation, this water is returned to the atmosphere through *evapotranspiration*. Finally, the portion remaining after runoff, evaporation, and evapotranspiration percolates downward to the *water table* and becomes what we define as groundwater.

In Chapter 2 we will see how the meteorological and geological conditions that determine groundwater patterns and their effect on landform changes over geologic ages. Many scientists believe that today we are in a warming trend, caused at least in part, perhaps, by the great quantity of fossil fuels being consumed. Some think the polar ice caps are diminishing; if that continues the sea levels can be expected to rise, with enormous impact on mankind's activities, including groundwater control.

Only a fraction of the precipitation falling on a given unit area of the earth's surface eventually becomes groundwater. Nevertheless, when we consider the enormous areas involved it is not surprising that the total volume of groundwater stored within the earth is very large. A common unit of water volume is the *acre-foot*, the quantity of water necessary to cover one acre to a depth of one foot. It equals about 43,500 ft^3 (1233 m^3). It is estimated that the total quantity of water on the earth, including the seas, is in the quadrillions (10^{15}) of acre-feet. The total freshwater is estimated at 33 trillion (10^{12}) acre-feet. This freshwater is distributed approximately as follows: 75% is locked in the polar ice caps, nearly 25% exists as groundwater, and less than 1% is in the rivers, lakes, and atmosphere. As we have said, a significant portion of this great terrestrial resource is in motion.

Figure 1.1 is a simplified illustration of the hydrologic cycle. Some study of it is helpful in understanding patterns of water movement. The runoff coefficient, that fraction of precipitation that moves directly across the land surface to the nearest stream, is a function of the slope of the terrain, the texture of the surface soils, the land use, and other factors. The rate of evaporation and evapotranspiration depends on soil texture, the type and density of vegetation, atmospheric conditions, and the like. The soil beneath the surface has an effect. Sandy, free-draining soils permit fairly rapid downward percolation of water. Clays and silts of low hydraulic conductivity tend to hold water near the surface in marshy areas so that a higher fraction is returned directly to the atmosphere.

There is a constant interchange between surface and ground waters. An effluent stream (Fig. 1.2a) drains the ground. Through springs and seepages along its banks and in its bottom, groundwater reappears as surface water. It is this effect that supports the flow of perennial streams during long periods of low precipitation. An influent stream (Fig. 1.2b), whose water surface is higher than the groundwater level, tends to recharge the ground. The same river can be both influent and effluent at different times and places. The Mississippi River in late summer at Saint Paul, Minnesota is usually draining the ground. But in early spring, with snow melt and heavy rains, the swollen river rises above the groundwater level and the flow recharges the ground. At New Orleans, Louisiana, further downstream, the Mississippi is retained within levees and essentially recharges the ground all year.

Groundwater itself is constantly in motion. The velocity is low in comparison to surface streams. Surface water velocities are measured in feet or meters per second—

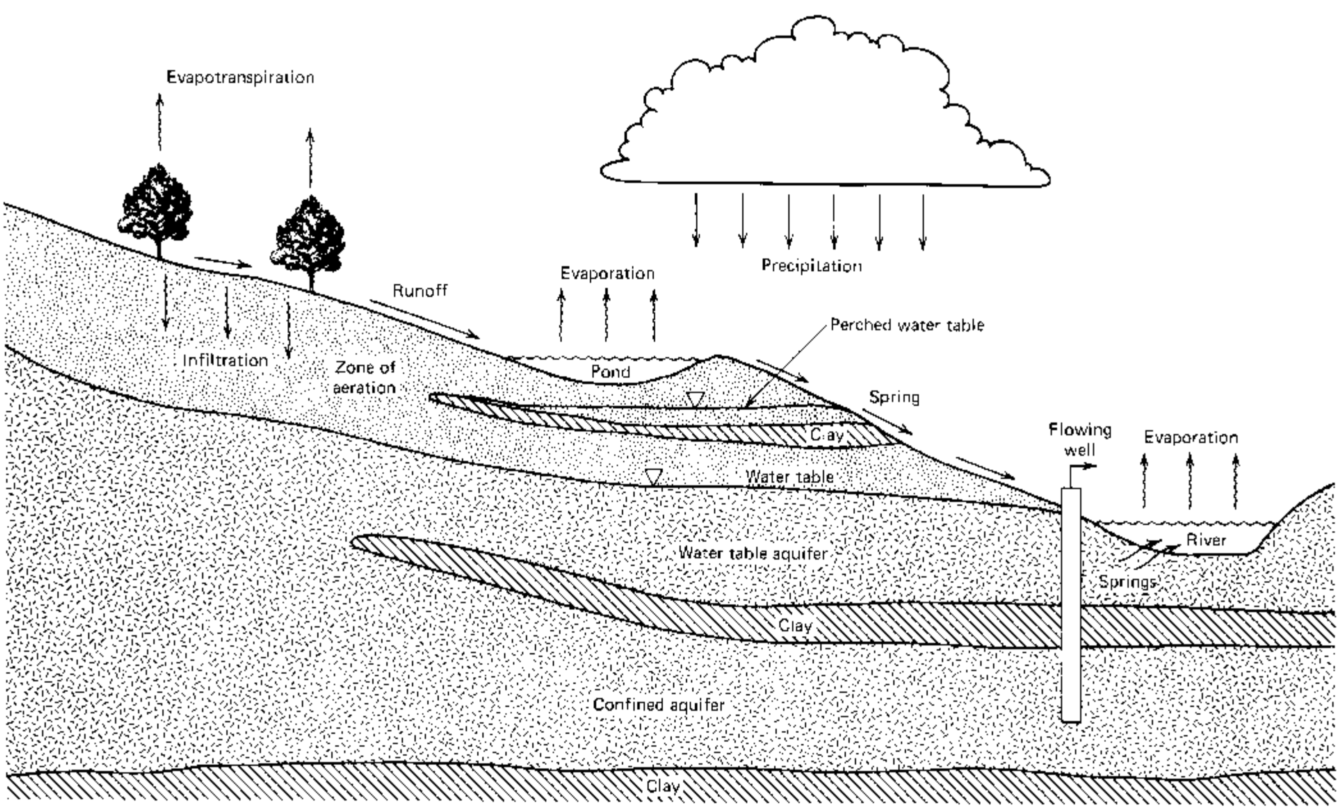

Figure 1.1 The hydrologic cycle. A part of the precipitation falling on the surface runs off toward the farm pond or the river, where some is evaporated and returned to the atmosphere. Of that part filtering into the ground, some is removed by the vegetation as evapotranspiration. Some part seeps down through the zone of aeration to the water table. Below the water table the water moves slowly toward the stream, where it reappears as surface water via springs in the streambed. Water in a confined aquifer can exist at pressures as high as its source, hence the flowing well. Water trapped above the upper clay layer can become perched, and reappear as a small seep along the riverbank.

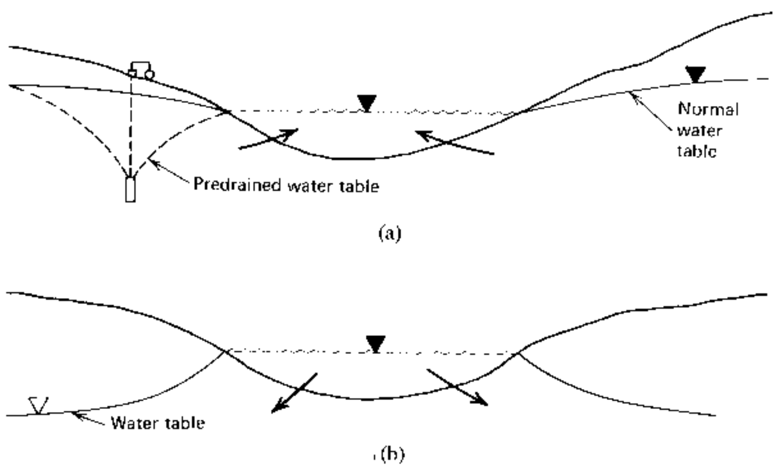

Figure 1.2 (a) Effluent stream. Normally groundwater flows toward the stream, which is acting as a drain. However, if a dewatering system is operated as shown at left, the flow is reversed. (b) Influent stream. The water in the stream, with its surface above the groundwater table, flows toward the ground.

groundwater in feet or centimeters per day. Pumping, however, changes normal groundwater flow patterns; velocities increase sharply, sometimes approaching several feet per minute in the immediate vicinity of wells.

Below the water table we say the soil pores are essentially saturated with water. A more precise definition of the water table is difficult. Above the water table, soil moisture exists as disconnected droplets and capillary films, while a substantial portion of the voids are filled with air. Below the water table, the water body is essentially continuous, except for an occasional bubble of air. Obviously, the transition from one to the other is not an abrupt plane, but a gradual zone. An observation well placed in the soil will indicate a "water level," sometimes referred to as the *phreatic surface*. In uniform aquifers the phreatic surface is a reasonable definition of the water table, provided that we understand its position can be modified by the effective size of the soil pores, by internal stresses in the soil, by the pattern of movement of groundwater particularly during periods of change, by the atmospheric pressure, and by the chemical and physical characteristics of the water itself. So, much can be said for uniform aquifers. In the stratified soils that nature normally presents us with, the indicated phreatic surface in an observation well can be an average of several water tables and may have no physical significance. So we can see that the water table is far from a simple concept; its measurement, and the evaluation of its significance to a construction project, can be complex. Refer to Chapter 8 for a fuller treatment of water table measurement.

An *aquifer* is a zone of soil or rock through which groundwater moves. A *confined aquifer* is a permeable zone between two *aquicludes,* which are confining beds of clay, silt, or other impermeable materials. The development of a confined aquifer is illustrated in Fig. 1.1. Water that infiltrates the soil in the uplands gradually moves downward, eventually becoming trapped beneath an upper confining bed of clay. Depending on the elevation of the water source, and the hydraulic conductivity and rate of flow in the aquifer, the pressure in confined aquifers can rise to considerable height. Sometimes the head rises above ground surface so that artesian, or flowing, wells can be constructed in the aquifer. The pressure in a confined aquifer will vary considerably depending on the rate of replenishment, the rate of discharge, and other factors, but the quantity of water stored in the aquifer changes only slightly.

In a *water table aquifer* there is no upper confining bed. The water table rises and falls with changing flow conditions in the aquifer. The amount of water stored in the aquifer changes radically with water table movements. This storage effect is of great significance to construction dewatering.

A *perched water table* occurs when an impermeable layer of clay or silt blocks water seeping downward and saturates the sand above it, as shown in Fig. 1.1, and water remains trapped above the perching layer. The sand below the clay is not saturated, so that the perched water is disconnected from the main ground water body. Perched water is typically of limited quantity, replenished or recharged very slowly. When encountered in an excavation, perched water will typically drain off very quickly, with limited continuous flow or bleeding, unless a source of recharge, such as a leaking utility, is present.

To summarize, we must conceive of groundwater as being in slow but constant motion; there is movement of water within aquifers and interchange of water between aquifers. There are continuing additions to the groundwater body by infiltration from the ground surface and by recharge from lakes and influent streams. There are continuing subtractions of groundwater by evaporation and evapotranspiration, by seepage into effluent streams, and by pumping from wells.

Patterns of groundwater movement change from time to time with changes in climate and with natural changes in topography due to erosion and deposition. And, of course, mankind's activities have been modifying the groundwater situation for millennia. Land drainage projects lower the water table, dams and surface reservoirs encourage infiltration, and when a river is confined within levees infiltration is reduced. With man's wells for water supply and irrigation, enormous quantities are withdrawn from the groundwater reservoirs.

When mankind converts the land surface from woodland to farm, the recharge by infiltration is reduced. When the farmland becomes covered with paved streets and buildings, recharge is reduced to very small levels.

Our activities in construction dewatering usually cause only temporary modification in groundwater patterns. But the structures created can make permanent changes.

1.2 ORIGINS OF DEWATERING

Human efforts to control water predate recorded history. Amid the ruins of the great civilizations of Babylon and Egypt, we find evidence of large aqueducts and even water tunnels. Many of the works were intended to supply water, but there were also land drainage projects to convert fetid marshes into arable land. Indeed, the construction of the water supply works must have entailed some form of what we call dewatering. The biblical well of Jacob required excavation below the water table, and presumably some means to control the water during digging was developed. The ancient waterworks depended on gravity for transportation where possible. Lifting water, when unavoidable, was done manually with buckets until mechanical devices were gradually developed (Fig. 1.3).

The Dutch polders are great stretches of fertile land below sea level protected by dikes. The inhabitants of the Rhine delta have struggled with the North Sea for many centuries; the early dikes predate the Romans. When water is resisted by a dike, seepage through the dike and rain falling inside its protection must be pumped away. There is evidence that in what is now the Netherlands the work was done first by slaves, and later by animals on wooden treadmills. Then people learned to harness the wind with devices so successful that picturesque windmills dot the countryside to this day, although few are still in dewatering service behind the dikes.

The search for gold, silver, and precious stones, and for useful materials such as copper and iron, sent people burrowing into the earth, and into direct conflict with groundwater. By the eighteenth century, with the dawn of the Industrial Revolution, the demand for coal was justifying elaborate efforts to recover it. The British coal mines pushed deeper and into more difficult water conditions. Endless rope conveyors powered by horses on treadmills removed water in buckets. In the 1770s, James Watt set in motion a train of events that was to result in our modern pumping systems. Many of Watt's early steam engines were used in mine dewatering. They were clumsy devices by modern standards; the cylinder was made of wooden staves and the piston was wood with canvas packing. Steam in the cylinder was condensed by water injection. Vacuum moved the piston and a wooden linkage transmitted the power to the bucket conveyor. Watt's economic studies convinced owners that the cost of the engine, plus the cost of the coal it consumed and the men who tended it, was less than buying and feeding horses. Naturally, Watt rated each engine by the number of horses it replaced. The term horsepower persists to this day in both the English and metric systems.

1.3 DEVELOPMENT OF MODERN DEWATERING TECHNOLOGY

The practical inventions of Watt and his contemporaries came about because of a fundamental change in man's con-

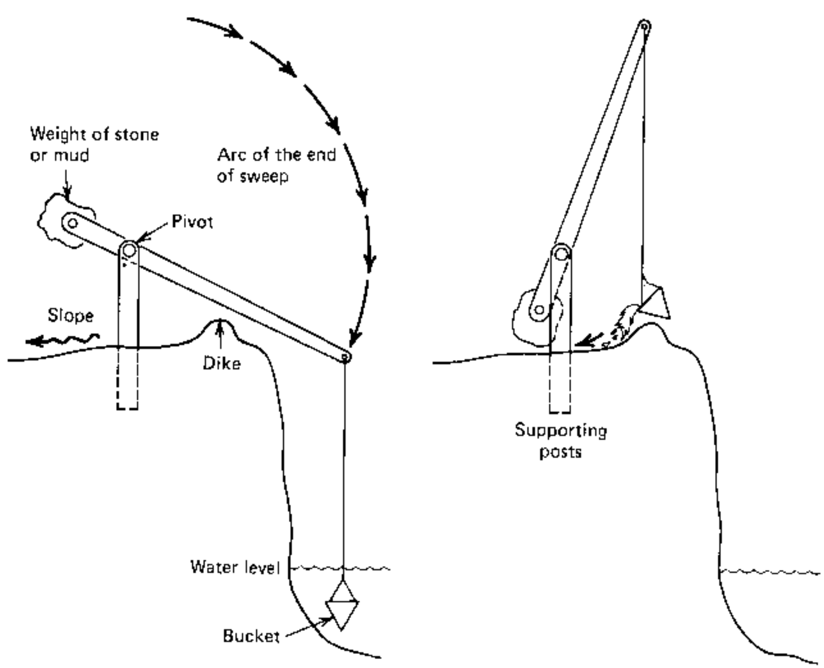

Figure 1.3 An early pumping device: the shadoof of the Middle East.

cept of the physical sciences. Ancient beliefs were challenged, as exemplified by Galileo and da Vinci in the Renaissance, and Descartes and Newton in the Age of Enlightenment. No longer were natural phenomena to be accepted as mysterious and unknowable, but questioned, observed, and studied until the laws governing natural forces could be understood. When the philosophers and scientists had made progress in the understanding of natural laws, the engineers and technologists of the Industrial Revolution made use of those laws to meet the needs of a burgeoning civilization.

While the scientists were making discoveries in mechanics, chemistry, physics, and electricity, and the engineers were achieving great progress in construction, manufacturing, transportation, and communication, the understanding of groundwater remained dim. Well into the twentieth century, our laws reflected the common belief that underground seepage was "unknowable," and the courts refused to intervene in groundwater disputes. As recently as 1997, a book was published purporting to be a serious treatment on "dowsing" or "water witching." Clever people still collect fees for locating underground streams by the manipulation of forked sticks, brass rods, or pendulums.

Explanations for the sluggish progress in understanding hydrology come readily to mind. In the simplest aquifer situations, the mathematics of groundwater flow are complex. And most natural aquifers are far from simple, as will be seen in Chapter 5. Observation of groundwater levels is difficult, expensive, and often confusing. Orderly patterns are not easy to discern. We cannot "see" the groundwater moving until it emerges into a stream or an excavation.

And, so, the subject remained generally shrouded in mystery although some progress was being made. Darcy stated his law of fluid flow through porous media in 1856. But this science of hydrology did not reach maturity until determined people, faced with problems of major economic significance, demanded a reasonable explanation for the observations they were making.

Robert Stephenson, the great British bridge and railroad builder, drew some strikingly pertinent conclusions during his work on the Kilsby Tunnel of the London and Birmingham Railway in the 1830s. Stephenson's tunnel encountered quicksand, and after some false starts he succeeded in stabilizing the sand with a series of 13, engine-driven wells pumping 1800 gpm (6800 L/min). Stephenson made careful observations of the groundwater level in shafts, in boreholes, and in the tunnel face itself. He concluded that there was a slope to the groundwater table created by his pumping and the slope was related to the resistance of the sand to water flow.

The Kilsby tunnel was a very early application of *predrainage,* that process of removing water from the soil by wells, wellpoints, or other devices in advance of the excavation. No doubt there were earlier applications. But in his work, Stephenson made observations in an effort to understand the process more clearly. His conclusions seem overly simplistic but they are quite in agreement with modern hydrologic concepts.

Predrainage with wells continued to be applied in the nineteenth century, especially in Europe. But wells are normally successful only in favorable aquifer situations and no doubt there were many failures. It would be decades before wells with submersible electric pumps would be utilized for dewatering work. At the end of the century, *wellpoints* began to appear. These small-diameter wells, driven into the ground and connected to a common suction manifold, were suitable for shallower aquifers where conventional wells had difficulty functioning. Wellpoints were used successfully in clean, fine to medium sands in Gary, Indiana, in 1901, and in similar soils in Atlantic City, New Jersey, in succeeding years.

In 1925, Thomas Moore, a builder of trench machines, encountered difficult water conditions on a sewer project in Hackensack, New Jersey. The soil was a very fine silty sand to sandy silt and driven wellpoints clogged up immediately. Moore introduced several innovative concepts: he used wellpoints with high infiltration area, he jetted the wellpoints into position, thus providing a large hole with clean sides, and he backfilled the hole around the wellpoint with selected filter sand. The fine-grained soils were effectively stabilized.

Moore's success in New Jersey demonstrated that predrainage under very difficult conditions was practical, and dewatering techniques began to develop rapidly (Fig. 1.4). Self-jetting wellpoints with ball valves and rugged screens capable of repeated installation were introduced. The original wellpoint pumps were diaphragm or piston-type positive displacement units. These were replaced with higher-capacity centrifugal pumps, continuously primed by positive displacement vacuum pumps. Installation methods began to include holepunchers, casings, higher-pressure jetting pumps, and air compressors. As the equipment improved, engineers and contractors attempted bigger and deeper excavations, under increasingly difficult conditions. Much experimentation was done at the jobsite, on projects already under way. But it was soon recognized that the art of dewatering had to be reduced to a more scientific basis if predictable success was to be assured.

By the end of the 1930s, engineers in the growing dewatering industry, like Thomas C. Gill and Byron Prugh, were recording and analyzing their observations. The pioneers in soil mechanics—Terzaghi, Arthur and Leo Casagrande, Taylor, Peck, and others—were proposing theories and conducting laboratory investigations.

As early as the 1920s, Meinzer was organizing relationships that could be used to understand groundwater flow. In the 1950s, impelled by the growing economic significance of groundwater for water supply and irrigation, hydrologists like Muskat, Theis, Jacob, Hantush, and others were developing practical techniques for aquifer testing and analysis. These methods were later adapted to the solution of dewatering problems. Some dewatering problems defied solution by analytic techniques until powerful personal com-

Figure 1.4 An early wellpoint system (c. 1928). Courtesy Moretrench.

Figure 1.5 In 1930, Moretrench demonstrated the use of wellpoints at the Road Show in Atlantic City, New Jersey, lowering the water table next to the Boardwalk by 22 ft (6.7 m). Courtesy Moretrench.

puters and software appeared in the 1980s. Now approximate numerical solutions are available.

New equipment and techniques for deep well construction, developed for oil exploration and for water supply wells, made wells a more practical tool for dewatering. Improved well screens and better understanding of gravel pack criteria made wells more efficient and suitable for less favorable soils. Improved drilling methods, such as the rotary, the reverse rotary, the down-the-hole drill, and the bucket auger, became available. The submersible electric motor, first developed for military use in Russia in 1915 and used in the dewatering of the Berlin subway in the 1920s, is the most popular device for dewatering well service today. As will be seen in Chapter 18, today's improved well equipment and well construction techniques, together with better methods of aquifer analysis, make possible the dewatering of many projects with wells where the method would have been unsuccessful only a few decades ago.

The ejector system (sometimes referred to as an eductor system) for dewatering was adapted from the domestic jet

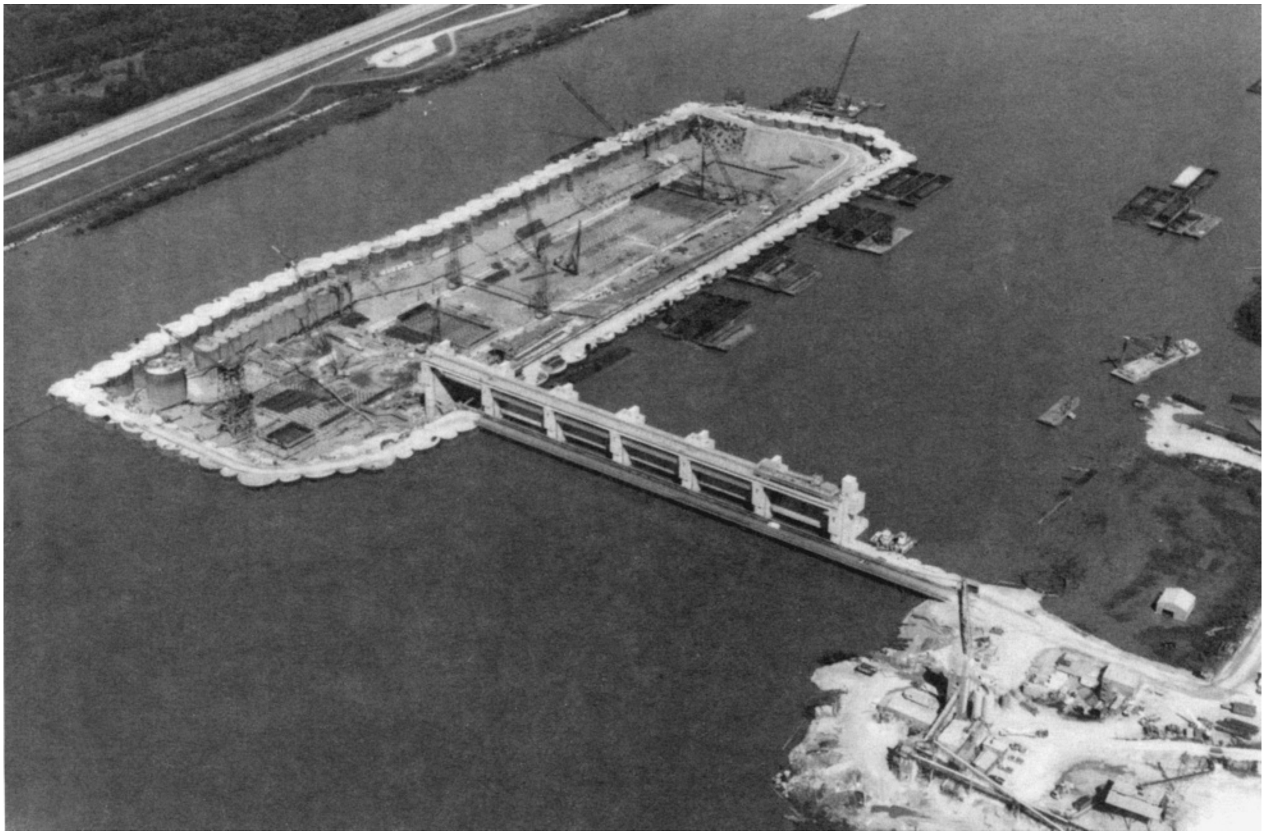

Figure 1.6 A multi-stage system of suction wells maintained a dry subgrade up to 86 ft. (26.2 m) below the Mississippi River, pumping up to 100,000 gpm (37,850 L/min). Courtesy Moretrench.

pump in the late 1950s. As discussed in Chapter 20, it is a most effective tool in certain job situations.

Coincident with improvements in dewatering technology and equipment, other methods of groundwater control have been developed. Grouting with cement, bentonite cement, or sophisticated permeation grouts using better techniques such as tube à manchette pipes can, with careful quality control, be used to cut off groundwater. Cast-in-place slurry walls, jet grouting, and ground freezing have been used successfully to both cut off groundwater and support the sides of an excavation. Slurry trenches can cut off water flow. Electro-osmosis can reduce the moisture content of, and strengthen, fine-grained silts and clays. Sand drains and wick drains have proven useful in relieving pore pressure in fine-grained compressible soils during consolidation. Each of these methods has had some degree of success in the specific job conditions to which they are suited.

With the advances that have been achieved in the more than 80 years since Thomas Moore first jetted his wellpoints to control quicksand in New Jersey, much of the mystery that once enshrouded groundwater has dissipated. But construction dewatering has not yet been reduced to an exact science. It is doubtful that it will ever be. The soil materials, the sources of water, and the demands of the project are too variable to be precisely analyzed. Any conclusions we base on theory must always be tempered by judgment and experience. The successful practitioner in dewatering will be the person who understands the theory and respects it, but who refuses to let theory overrule judgment. When theoretical conclusions coincide with judgment, the dewatering engineer can proceed with the program with confidence. When there is disagreement, caution should be used until the discrepancy is understood.

With appropriate regard to both theory and practical judgment, effective dewatering can be accomplished under almost any field conditions (Fig. 1.6). However, because of the uncertainties of the underground, any proposed dewatering program must be flexible, with provisions for modification if unexpected conditions are encountered. In the experience of the authors of this book, it is atypical that a dewatering system, installed as it is designed, is successful without any modification. Flexibility is a key element in success.