CHAPTER 1

CIVIL ENGINEERING SYSTEMS AND THEIR EVOLUTION

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1.0 INTRODUCTION

This chapter starts by defining civil engineering and describes briefly the current and future practices of the different civil engineering disciplines. The historical evolution of each civil engineering discipline is featured prominently in this chapter because it is also important for today's civil engineers to acknowledge the profession's trailblazers and appreciate their contributions to the growth of the profession. We will show how the evolution of civil engineering, as well as other disciplines related to civil engineering, have been shaped by changes in human value systems, interactions between the profession and socioeconomic forces, advances in science and technology, and innovations in materials, equipment, and the like. Civil systems engineering is not a new practice; on the contrary, over the ages, civil engineers or persons serving in that capacity have always executed their work from a systems perspective, perhaps at times implicitly. In this text, we will argue that the civil engineering discipline could be further enhanced if the development of its systems explicitly incorporates new analytical tools in systems engineering. This is particularly important in the current era, with its high population growth demanding new civil systems and increased need for preserving aging civil infrastructure, at a time when funding constraints are a stark reality, stakeholders are more involved in the development process, and users have higher service expectations.

1.1 CIVIL ENGINEERING SYSTEMS AND HISTORICAL DEVELOPMENTS

1.1.1 The Importance of Studying the History of Engineering Systems

Eminent historians agree that the extent to which the history of a profession is known, preserved, honored, and utilized greatly influences the degree to which the profession knows and comprehends itself; and it also dictates the extent to which the profession is acknowledged and respected by others outside its confines. This applies no less to the engineering profession, where, in spite of its long and rich history, many skilled engineers today tend to be dismissive of their heritage and instead focus solely on state-of-the-art or current trends in their specialized areas of practice. As such, the history of engineering is often relegated to a minor or nonexistent role in professional development conferences and in formal engineering education.

Fortunately, many prominent civil engineers in the current era believe that knowledge of engineering history will lead to a reinforcement of the profession and its stature among other professions, specifically, that civil engineering has a deserved place in the arena of the overall evolution of civilization and the world. Furthermore, knowing the history of engineering systems enables those who practice engineering to better understand the simultaneous relationship between engineering and other sectors of human development, such as health, agriculture, and industry. Also, the history of engineering, from the inspiring narratives of great projects as well as the seemingly small incremental improvements, provides illumination and caveats about what was once thought to be the state of the art and should be recognized as fundamental knowledge rather than irrelevant to the current state of the art (Petroski, 2001).

The purpose of any documentation of history is to interpret the development and activity of humankind (Kirby et al., 1956). As such, the history of engineering systems is but one aspect of the overall narrative of the human experience. However, unlike many other aspects of this experience, the history of engineering records a human activity that is cumulative and progressive because its evolution is characterized by successive building upon previously existing knowledge. The history of engineering systems therefore depicts a dimension of the overall theme of history that mirrors the development of civilization over the millennia. According to engineering historians, the historical evolution of engineering is best understood when it is discussed in the context of other transformative events of history that changed the way humans live: the food production revolution (circa 6000–3000 BC), the emergence of urban communities (circa 3000–2000 BC), the birth of Greek science (600–300 BC), innovations in power generation in Europe (in the Middle Ages), the development of modern science (17th century), the Industrial Revolution (18th century), the invention of electricity and the advent of applied science (19th century), and the current age of automation and information technology (20th and 21st centuries).

1.1.2 Engineering Definitions and General Evolution of Civil Engineering

Civil engineering is best defined in the context of engineering systems in general, and this section will first present general definitions of engineering and then move on to specific definitions of civil engineering. A simple definition of engineering is *the application of science, mathematics, business, and other fields to harness efficiently the resources of nature to develop structures and facilities that benefit the entire society at the current time and in the future*. Other definitions provided by White (2008) and Moncur (2012) include:

- The art of directing the great sources of power in nature for the use and convenience of humans (Thomas Tredgold, 1828)
- A triad of trilogies (first trilogy—pure science, applied science, and engineering; second trilogy—economic theory, finance, and engineering; third trilogy—social relations, industrial relations, and engineering) (Hardy Cross, 1952)
- The art of the organized forcing of technological change … engineers operate at the interface between science and society (Dean Gordon Brown, year unknown)
- The innovative and methodical application of scientific knowledge and technology to produce a device, system, or process that is intended to satisfy human need(s) (Gerard Voland, 1999)
- The art of organizing and directing men and controlling the forces and materials of nature for the benefit of the human race (Henry Stott, 1907)
- Realization of a figment of imagination that elevates the standard of living and adds to the comforts of life (Herbert Hoover, year unknown)
- Activities that make the resources of nature available in a form beneficial to humans and provide systems that will perform optimally and economically (Llewellen Boelter, 1957)
- Activity other than purely manual and physical work that brings about the utilization of the materials and laws of nature for the good of humanity (Rudolf Hellmund, 1929)
- The professional art of applying science to the optimum conversion of natural resources to the benefit of humans (Ralph Smith, year unknown)

- The practice of safe and economic application of scientific laws governing the forces and materials of nature by organizing, designing, and constructing for the general benefit of humankind (S. Lindsay, 1920)
- The art or science of making practical (Samuel Florman, year unknown)
- Visualization of the needs of society and translating scientific knowledge into tools, resources, energy, and labor to bring them into the service of humans (Sir Eric Ashby, year unknown)
- The professional and systematic application of science to the efficient utilization of natural resources to produce wealth (Theodore Hoover and John Fish, 1941)
- The science of economy, of conserving the energy, kinetic and potential, provided and stored up by nature for the use of humans … [utilizing] this energy to the best advantage, so that there may be the least possible waste (William Smith, 1908)
- Application, with judgment, of the knowledge of the mathematical and natural sciences, gained by study, experience, and practice, to develop ways to utilize, economically, the materials and forces of nature for the benefit of humankind (The Accreditation Board for Engineering and Technology, Inc., 1993)

For the civil engineering discipline specifically, formal definitions date back to 1828 when the charter of the Institution of Civil Engineers (ICE), in the United Kingdom defined that discipline as: The art of directing the great sources of power in nature for the use and convenience of man, as "the means of production and of traffic in states, both for external and internal trade, as applied in the construction of roads, bridges, aqueducts, canals, river navigation, and docks for internal intercourse and exchange, and in the construction of ports, harbors, moles, breakwaters, and lighthouses, and in the art of navigation by artificial power for the purposes of commerce, and in the construction and application of machinery, and in the drainage of cities and towns" (ICE, 2007).

In 1961, the American Society of Civil Engineers defined civil engineering as: "The profession in which a knowledge of the mathematical and physical sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the progressive well-being of humanity in creating, improving, and protecting the environment, in providing facilities for community living, industry and transportation, and in providing structures for the use of humanity."

In the definitions above, it is possible to discern the recurrence of certain concepts that the reader will recognize later in this text as systems engineering concepts. An example is the ***application of scientific tenets*** (Voland). In fact, classical science, which stipulates that all scientific inquiry should be rooted in hard facts, experimentation and objective analysis, and inferences, is a key aspect of system engineering. The role of science in civil engineering is evidenced in the definitions above through the use of such phrases as *through the aid of science*, *utilization of the laws of nature, art of applying science, application of scientific laws*, and *systematic application of science* are evidential of the role of science in civil engineering. Civil engineering is considered a science because its practice is consistent with the key characteristics of the classical scientific method—hypothesis setting and testing, replicability, refutability, and reductionism (Khisty and Mohammadi, 2001).

Other evidence of systems engineering concepts in the above definitions includes the phrase ***broad range of criteria*** for analyzing and evaluating engineering systems, which includes reference to the engineer as *one who uses the knowledge in all disciplines, including sociology* (Doherty), or *one who operates at the border between science and society* (Brown). This suggests that engineering is not only a science but also goes beyond the tenets of classical science, and thus in the course of their work, engineers typically examine problems from a broad range of criteria, not just those that are science based.

The **optimization of resources**, another systems engineering concept, has long existed in engineering practice as can be observed in the above definitions. For example, in their definitions of engineering, William Smith utilizes words such as *least possible waste* and *best advantage*; Hoover and Fish talk of *efficient utilization*; Ralph Smith makes reference to *optimum conversion*; and Boelter uses words like *perform optimally*.

The **ethical responsibility** of engineers is evident in the description of engineers as *persons who operate at the interface of science and society* (Brown) and the use of phrases such as *benefit of the human race* (Stott), *comforts of life* (Boelter), *good of humanity* (Helmund), *benefit of man* (Smith), *benefit of mankind* (Lindsay), and *needs of society* (Ashby).

Against the background of the definitions, we will now discuss the evolution of civil engineering as a discipline. Historians believe that the discipline took root between 4000 and 2000 BC when humans in ancient civilizations began to abandon their nomadic lifestyles in favor of more permanent shelter, thus generating the need for fixed facilities and structures. The reshaping of caves to protect humans from harsh weather and the use of tree trunks to cross water bodies were early practices related to civil engineering (Straub, 1964). Consequently, a need arose to transport large amounts of goods to and from human settlements for purposes of consumption, trade, and warfare. This also led to the need for roads and water-bearing and water-transporting structures such as aqueducts and canals. The new lifestyle generated other needs such as cultural (tombs for kings), religious (altars and temples), and entertainment facilities (large fighting arenas). Arguably, the first people to develop engineering systems were the Sumerians (located in present-day Iraq, 4500–1700 BC approximately) who constructed an intricate hydraulic system comprised of canals, dams, reservoirs, and weirs that helped transform their arid landscape into a systematic and lush city with beautiful gardens and fertile lands (Kramer, 1963). Other notable large engineering structures that date back several thousand years include the pyramids of Egypt constructed during 2800–2400 BC (Smoothwhirl, 2009) and the Great Wall of China (circa 200 BC).

The BC–AD transition millennium (500 BC to AD 500) was marked by significant advancements worldwide, including ancient civilizations in Persia, Greece, South America, South Asia, China, and Africa. In 3 BC, in what was probably the first scientific approach to the physical sciences applied to civil engineering, Archimedes established the laws of buoyancy and constructed a large screw that raised water from lower levels. Also in that era, impressive civil structures were constructed by a number of ancient civilizations worldwide including qanats (irrigation structures) in present-day Iran, the stupa monasteries in present-day Sri Lanka, and ancient structures in Great Zimbabwe. During the time of the Roman Empire (circa 27 BC to AD 500), extensive civil structures were constructed that included aqueducts, bridges, and dams. Other civilizations that were marked by remarkable achievements in civil engineering included those of Greece, Harrapan (in present-day India and Pakistan), and Maya (in present-day Mexico).

In all these and other civilizations that spanned the course of history, civil engineering systems have been developed in a bid to enhance the quality of life of people, for example, to provide water for irrigation and for drinking; dispose of liquid waste; and transport goods, message-bearing emissaries, and equipment and soldiers for defense purposes. Also, the development of civil engineering systems has proceeded in parallel with the advancements in other devices associated with the use of these systems. For example, the development of horse-drawn chariots provided greater impetus for improvements in road pavement construction.

The development of civil engineering as a profession has been evolutionary and incremental. The etymological root of the word “engineer” is the Latin word “ingenium”, which means talent or mental power (Lienhard, 2000), and also was the name given to an ingenious device used by the Roman army to attack fortifications (Dandy et al., 2008). The field of civil engineering is considered the oldest nonmilitary engineering discipline and one of the oldest among all professions worldwide. The earliest engineers that carried out civil works actually were military engineers who possessed expertise in infrastructure of both military and civil purposes. In times of war, these engineers used their expertise to help facilitate conquests or defense by building catapults, observation towers, bridges across rivers, and other military facilities. In times of peace, however, their expertise was used for civilian purposes for the benefit of the populace. At some point in history, a dichotomy was established between military and nonmilitary engineers [Encyclopedia Britannica (EB), 2011]: The term *civil engineer* was used to describe any engineer who did not practice military engineering.

A drawn-out but perceptible watershed in the development of the profession was the formalization of design calculations. Over the centuries, design rules of thumb and empirical formulas used by civil engineers were gradually supplanted or supplemented by standardized design and numerical analyses, and the knowledge acquired through experience was documented and codified. Furthermore, stonemasons and craftsmen, who were mostly self-taught but skilled, acquired specific titles that indicated societal recognition of their skills (EB, 2011). The Renaissance in Europe (1500–1800) was characterized by prosperous urban societies that fueled the demand for infrastructure and technology. This period saw a rapid pace in the development of civil engineering as a profession in France as evidenced by the establishment of state-planned infrastructure by ministers in the Bourbons era (Chrimes and Bhogal, 2001); the first engineering school in modern times, the National School of Bridges and Highways was opened by Perronet in France in 1747; in Paris in 1794 and in Berlin in 1799, the École Polytechnique and the Bauakademie, respectively, were founded. John Smeaton of England was the first person to actually call himself a "civil engineer." In 1818, the Institution of Civil Engineers, the world's first engineering society, was founded in London; and in 1828, it was awarded a royal charter that formally recognized civil engineering as a profession. In the United States, Benjamin Wright, considered the father of American civil engineering, helped design and construct the Erie Canal and several railroads in the 19th century (FitzSimons, 1996). In the 19th and 20th centuries, persons calling themselves civil engineers in the United States and Europe designed and built all types of structures, water supply and sewer systems, railroads, and highways and planned cities. Notable civil engineers in that era included Benjamin Baker, Marc and Isambard Brunel, Gustave Eiffel, John Fowler, John Jervis, Robert Maillart, John Roebling, and Thomas Telford. The American Society of Civil Engineers (ASCE) was founded by 12 engineers in a meeting at the Croton Aqueduct administration offices in New York City on November 5, 1852 (ASCE, 2009). In the 20th century, professional civil engineering organizations with various designations including societies, institutes, and orders were formed in countries worldwide to advance the profession, protect the interests of members, and foster positive interactions with the general public.

Over the last two centuries, the role of civil engineers has been rather explicit and distinguishable from that of other related professions as they have applied their knowledge to plan, design, build, maintain, or/and operate complex civil infrastructure systems that have served humankind in a variety of ways. These systems include buildings for residential, commercial, and industrial purposes; facilities for transporting passengers and freight; and networks for transporting water, storm water, or wastewater. Specifically, civil engineers have responsibilities for constructing and/or managing a wide array of system types, including water and wastewater treatment plants, storm water and wastewater drainage, dams and levees, power plants, highway pavements and bridges, railroads, pedestrian and cyclist facilities, irrigation and shipping canals, river navigation, traffic infrastructure, public transit guideways and terminals, airport runways and terminals, transmission towers and lines, tunnels and industrial plant structures. Depending on the type of system or structure in question, the practice of civil engineering often involves some knowledge of other fields, such as physics, mathematics, geography, geology, soil science, hydrology, and mechanics. Consequently, the development of civil engineering has followed the progress made in these other fields; and in recent decades, the advancement of civil engineering systems management has followed the trends in economics, finance, statistics, and operations research.

The development of civil engineering systems has been a catalyst in the socioeconomic transformations we are experiencing today. Thus, civil engineering is one of the most effective vehicles for quality of life improvements for humankind. Social and economic changes constantly create new demands on civil engineers, who respond by fabricating, maintaining, and operating civil engineering systems to fulfill the needs and desires of society. As such, civil engineers actively and specifically seek engineering decisions that ultimately benefit, or at least minimize conflicts with, the social and economic environments. Dandy et al. (2008) pointed out that the relationship between engineering and society even transcends the physical realm and that part of the cultural character of regions and major cities can be attributed, at least in part, to iconic civil engineering structures at such locations. Examples include the Panama Canal, London's Big Ben Tower, Paris' Eiffel Tower, Rome's Coliseum, Greece's Parthenon, China's Great Wall, Sydney's Harbor Bridge, Egypt's Suez Canal, India's Taj Mahal, and New York's Statue of Liberty.

In the next section, we discuss key historical developments in the different branches of civil engineering in various civilizations over the course of human history.

1.2 CIVIL ENGINEERING SYSTEM—THE BRANCHES

Civil engineering can be classified on the basis of the intended use of the facility [heavy, industrial, commercial, residential, and recreational (Figure 1.1)] and the branches of civil engineering (hydraulic, hydrologic, transportation, architectural, materials, construction, structural, geomatic, and geotechnical engineering). For each facility type, the construction directly involves the civil engineering branches of geomatics, architectural, materials, construction, structural, and geotechnical engineering; and the operations are directly associated with at least one of the following branches of civil engineering: hydraulic, hydrologic, transportation, architectural, and engineering.

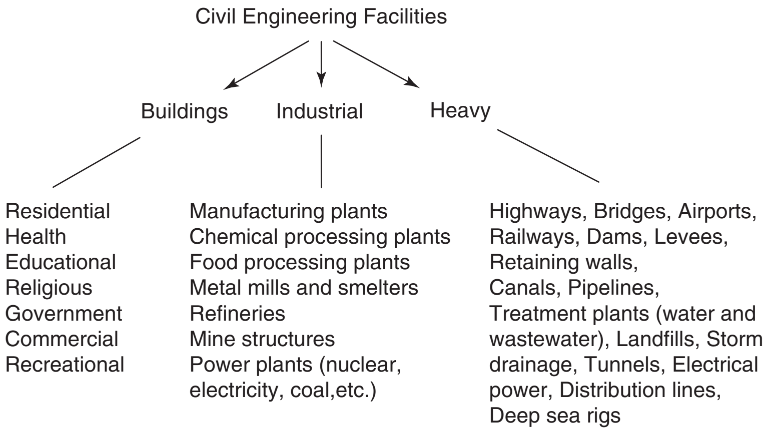


Figure 1.1 Categories of civil engineering facilities.

Intended Use of facility[1] / **Phase of Facility Development**	**Water (Treatment, Supply, Distribution**	**Transportation (Road, Rail, Water, Air)**	**Buildings (Residential, Commercial, Industrial, Recreational)**
Initial Stages (Planning and Designing the Facility)	Survey engineers, Structural engineers, Geotechnical engineers		
	Hydraulic engineers Environmental engineers	Transportation engineers	Architectural engineers
Implementation Stage (Constructing the Facility)	Construction engineers, Materials engineers		
	Environmental engineers	Transportation engineers	Building engineers
Usage Stage (Operating and Maintaining the Facility)	Water/Wastewater Treatment plant engineers	Transportation engineers	Building engineers

[1] *Of several facility types, only three are shown here: water, transportation, and buildings.*

Figure 1.2 Civil engineering branches categorized by phase of facility development and intended use of the facility.

The interface between the facility type and the civil engineering branch is influenced by the phase of the development of the facility in question. In other words, for any facility associated with a branch, the sequence of development goes through several phases including planning, design, construction, operations, and maintenance (Figure 1.2). Thus, there are engineers who work in phase-based branches, such as geotechnical engineers, who study the feasibility of soil support of a structure and design its foundation; structural engineers, who design the structure to withstand loads; construction engineers, who build the structure; and system operations engineers such as water plant managers, who run the system; and maintenance engineers, who preserve system physical structures. On the other hand, certain civil engineering branches involve a single type of facility (e.g., highways, water treatment plants, etc.); and such engineers are concerned with all phases of these facilities, from planning and design to preservation and operations. In contrast to the phase-based branches, these function-based branches exist on the basis of the intended use of the system and include transportation engineering, hydraulic engineering, and environmental engineering.

Clearly, the expansive breadth of civil system types and the number of systems development phases make it difficult for any individual civil engineer to be skilled in all the different branches and phases. There is necessarily a great deal of specialization, therefore, even within the different branches of civil engineering. Overall, there are at least nine branches of civil engineering, each of which has seen an interesting evolution of development from ancient times to current day. We discuss briefly in the following sections, the nature of work and the pioneers for each branch of civil engineering as well as its historical roots, evolution over time, and future expectations.

1.2.1 Structural Engineering Systems

Any physical object that is intended to support or resist dead or live loads, and to dissipate energy, regardless of its ultimate purpose, is amenable to structural engineering analysis. Thus, structural engineers design and analyze load-bearing architectural or civil engineering structures including buildings, towers, bridges, tunnels, dams, and retaining walls, and noncivil structures including equipment, vehicles (land, sea, or air), and other structures where structural stability of integrity is critical for safety and servicability. One aspect of structural engineering is the decomposition of a structure into its constituent subsystems: columns, beams, plates, arches, shells, and catenaries, even though in some cases, it is more intuitive to analyze the entire multicomponent structure

Figure 1.3 El Alamillo Bridge (Seville, Spain), designed by structural engineer Santiago Calatrava, combines aesthetic performance with structural efficiency (Courtesy of Consorcio Turismo Sevilla).

as a system of systems. Using various materials including steel, concrete, composites, and other materials for their designs, structural engineers investigate the actual or predicted outcomes of their systems in terms of specified mechanical behavior and functionality, for example, performance criteria including safety (e.g., failure of its components), serviceability (e.g., discomfort to system users due to vibration, shaking, or sway), durability (e.g., satisfactory life with minimal maintenance), cost (e.g., optimal use of materials and resources), and in certain cases, aesthetics (Figure 1.3).

Structural analysis helps to ascertain the magnitudes and directions of forces and deformations in a structure due to dead and live loads; structural design determines the dimensions of the structural members to ensure that the structure is capable of supporting the intended loads. Simulation models, which we shall discuss in Chapter 13, are used widely in structural engineering and are intended to replicate, as closely as possible, the actual behavior of the structure as a function of its material properties, structural features, loading, and boundary conditions (Liew and Shanmugam, 2004).

The History of Structural Engineering Systems. The field of structural engineering has existed, albeit as an informal discipline, ever since humans first began to build their own permanent structures. At the height of their civilization (6000–2000 BC), the Sumerians in ancient Mesopotamia (present-day Iraq), designed and constructed large, layered platforms called *ziggurats* (Figure 1.4) for supporting their temples, similar to structures that were built in a later era by the Aztecs of Central America. It has been speculated that one of these Sumerian structures was the Tower of Babel that is described in the Book of Genesis in the Bible. The ziggurat architectural and structural style has inspired a number of modern buildings such as the University of Tennessee's John Hodges Library in Knoxville. The Sumerians also developed key structural elements, such as arcs and domes (which are used in current-day design) and utilized innovative structural techniques

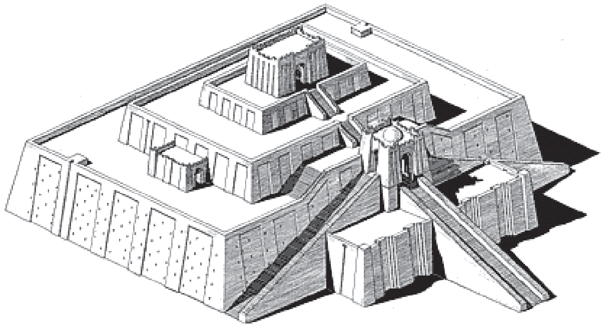


Figure 1.4 Ziggurats, structural systems comprising large, layered platforms, supported worship temples in ancient Mesopotamia and other civilizations several millennia ago (Wikimedia commons/United States Army).

such as buttresses, recesses, and half columns in building their temples and palaces (Shuter, 2008). In the Minoan civilization (circa 2700–1400 BC), column inversion (bottom width smaller than top width) and multiple-storey buildings were significant structural features of that era (Benton and DiYanni, 1998). Some engineering historians believe that the formal discipline of structural engineering began in 2700 BC when Imhotep (considered the first structural engineer in history) built Pharoah Djoser's pyramid. During ancient times and in the medieval era, the design and construction of structures were carried out by artisans similar to Imhotep, particularly carpenters and stonemasons, and officials in royal courts who held titles such as *master builder* (Saouma, 2007) and served as both the architect and structural engineer. According to historians, explicit theories of structures did not exist and there was limited understanding of how structures remained stable; knowledge was accumulated through experience and passed on over time through successive experts.

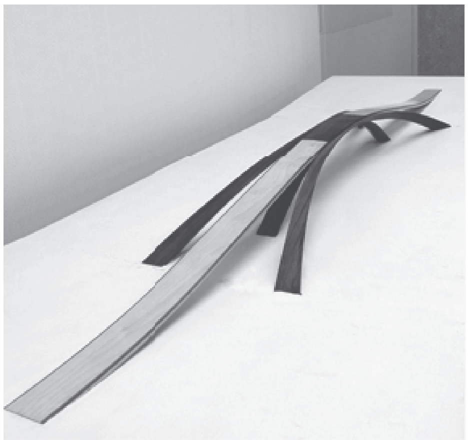
In ancient Greece (circa 220 BC), Archimedes calculated the areas and determined the centers of gravity of a number of geometric figures and developed calculus and Euclidian geometry, thus providing the mathematical foundations for current structural engineering theory. Also, in ancient Rome, Vitruvius, a famous Roman architect and engineer, in his 15 BC manual of civil and structural engineering, described the techniques used in planning, designing, and building a number of structures (Straub, 1964). During the ancient civilization of Great Zimbabwe in AD 11, a number of formidable civil engineering structures were designed and constructed in a style that "eschewed rectilinearity for flowing curves" (MetArt, 2009). During that era, significant contributors to formal structural engineering included Abu Rayhan al-Biruni and Abd al-Rahman al-Khazini. These Persian scholars helped build the foundations for the theory of structures by pioneering the application of experimental scientific methods to statics and dynamics and by unifying these two areas into the science of mechanics. They introduced algebraic techniques into the field of statics and were first to develop general center-of-gravity theory. In the Tibet region of China in AD 762, structural engineers designed iron bridges that included probably the first suspension bridge in history, which was constructed by engineer Thanstonrgyalpo, the *lcag zam pa* (the builder of iron bridges). Also, in China in the 15th century, bridges that were constructed generally utilized far less material than those of the preceding civilizations worldwide. Also, Chinese bridge builders of that era invented the complete circle structure (the arch of the bridge above being mirrored by a corresponding inverted arch below) that sprung from the same abutments deep under water, such as the Tung-Mei bridge constructed circa 1470 and still in use at least until 1970 and possibly today Needham et al., 2001. Such masonry rings afforded great stability at areas having weak natural foundations. In Italy in the early 16th century, Leonardo da Vinci produced a number of structural and other engineering designs.

The 17th and 18th centuries saw several watermarks in basic sciences that later laid the foundation for structural engineering. In 1658, Galileo published a seminal work that addressed the science of the strength of engineering materials and also pioneered the use of scientific approaches in structural engineering. Galileo's thesis ignited the field of structural analysis (defined as the mathematical representation and design of engineering structures). In 1678, the behavior of materials was first explained by Robert Hooke on the basis of the elasticity of materials, followed by the explanation of the fundamental laws governing structures by Isaac Newton. Several decades later, there were advancements in mathematical methods that facilitated the modeling and analysis of engineering structures. In that era, Leonhard Euler formulated the buckling equation that helped analyze structural elements in compression. Also in that era, Euler and Daniel Bernoulli developed the Euler–Bernoulli beam equation, a basic theory in the design of structures (Bradley, 2007), and the Bernoulli brothers provided analytical tools to analyze structures (Dugas, 1988).

In 1809, the first suspension bridge capable of carrying vehicles was built to cross the Merrimac River (a 250-ft span) in Massachusetts. Advancements such as this, catalyzed by significant discoveries in material science, structural analysis, and the physical sciences, helped structural engineering to evolve into a more formalized profession toward the end of the 19th century, particularly during the Industrial Revolution. In 1873, Carlo Castigliano developed methods for determining displacement as partial derivatives of strain energy through his thesis *Intorno ai sistemi elastici*. Advancements in concrete technology included Joseph Aspdin's 1824 invention of Portland cement, which made concrete construction economically feasible; the 1855 development of modern reinforced concrete by Joseph-Louis Lambot and William Wilkinson; and the 1867 use of steel reinforcement in regions of tensile forces in concrete structures by Joseph Monier (Prentice, 1990; Kirby, 1990; Nedwell et al. 1994). At the end of the 19th century and the early 20th century, advancements in cast iron technology facilitated steel bridge construction in Europe. Also, Vladimir Shukhov established methods for analyzing nontraditional structures such as those with unconventional shapes or thin shells. The new century saw developments in reinforced concrete shear design by Wilhelm Ritter and in the behavior of concrete as a linear-elastic material by Emil Morsch.

The 20th century saw further contributions to reinforced concrete science by innovators that included Swiss engineer Robert Maillart and enhancements in the design and analysis of steel and concrete structural systems through greater understanding of the plastic behavior of concrete. In 1928, the development of prestressed concrete by Eugene Freyssinet helped structural engineers address the weakness of concrete structures in tension. In 1930, Hardy Cross facilitated quick and accurate determination of stresses in complex structures through his moment distribution method, and in the 1950s, John Baker developed the plasticity theory of structures, thus facilitating the design of steel structures (Heyman, 1998). In the late 1960s and early 1970s, Fazlur Rahman Khan introduced innovations such as the "bundled tube" structural design for skyscrapers, which was used for Chicago's John Hancock Center and Sears Tower. Khan also developed the structural concept of X-bracing, which reduced lateral loads on a building by transferring such loads into exterior columns, thus reducing the need for interior columns and making more floor space available.

LEONARDO, THE VISIONARY BRIDGE ENGINEER



Conceptual model.

Bridge under construction, 2001, Vebjorn Sand, Norway.

In 1502, Leonardo da Vinci wrote a letter to Ottoman Sultan Beyazid II of Istanbul to propose the building of a single-span 720-ft (0.24-km) bridge over the Bosporus at a point known as the Golden Horn. Leonardo's preliminary drawings consisted of the classic keystone arc design; his design was based on the premise that by using a flared foothold and the terrain to anchor each end of the bridge, the arc could be stretched narrow and substantially widened without losing any structural integrity. Believing that such a construction was impossible, the Sultan did not build the bridge.

Since 1952 when the letter was discovered in Turkish National Archives at Istanbul, experts have pondered whether it would have been feasible to construct the bridge. So, by the Sultan's refusal to build the bridge, was Leonardo saved from disaster and professional ignominy? Or was he deprived of the legacy of possibly being the most innovative bridge builder of his time? In any case, engineering historians assert that Leonardo's Golden Horn Bridge design is "an eloquent synthesis of form and function typical of his universal thinking." Leonardo's vision was revisited in 2001 when his design was used to construct a smaller bridge in Norway (see photo). In 2006, a decision was made by the Turkish government to construct a bridge, using Leonardo's design, to span the Golden Horn estuary.

Sources: Atalay and Wamsley (2009). *Image source*: www.leonardobridgeproject.org, an organization that inspires human artistic, spiritual, and intellectual endeavor transcending cultural borders through the construction of Leonardo da Vinci's graceful Golden Horn bridge design.

Since the late 20th century, structural analysis has been enhanced by advancements in computing power. This has fostered the use of computational and numerical methods, including simulation and finite element analysis, to reliably estimate the engineering behavior of structural materials and complex structural configurations. These advancements have made it possible to develop increasingly bold structural systems such as London's Millennium Dome, Greece's Rion-Antirion Bridge, Shanghai's Nanpu Bridge, Japan's Akashi-Kaikyo Bridge, South Korea's Jongro Tower, and Jakarta's Regatta Hotel at the Pantai Mutiara Canal Estate. Others include Toronto's CN Tower, Sweden's Turning Torso Building, Italy's Strait of Messina Bridge, Barcelona's Montjuic Communications Tower, Spain's Alamillo Bridge, Beijing's Bird's Nest Stadium, and Dubai's Burj Khalifa, currently the world's tallest building. The shape of the Burj Khalifa (Figure 1.5) not only takes inspiration from indigenous desert flowers [Landmark Properties (LP), 2009] that also appear as

Figure 1.5 The Burj Khalifa, currently the world's tallest building, is a testament to current advancements in structural engineering (*Source:* Nicolas Lannuzel).

decorative patterns in Islamic architecture but also serves a technical purpose. In order to support the great height of the building, the engineers developed the "buttressed core," a new structural system that consists of a hexagonal core that is reinforced by three Y-shaped buttresses thus facilitating lateral self-support of the building and avoiding twisting [GulfNews (GN), 2010].

The Future of Structural Engineering Systems. The future of structural engineering will be guided in part by innovations in material science, boldness in design, desire for resilience to hazards, and computer technology. Ongoing advancements in structural materials, for example, through research in nanotechnology and materials science, will open up new directions in structural design from the perspectives of sustainability, economy, aesthetics, fire resistance, and durability (Ochsendorf, 2005). The past 50 years have seen strength improvements in structural steel (40%), reinforcing bar (50%), and concrete (at most 100%) (Magnusson, 2007). Further innovations in these materials are expected to continue and could include the development of stainless steel, fiber-reinforced polymers, and other materials for steel construction and concrete reinforcement. Concrete research continues to yield high-performance concrete (HPC), such as translucent concrete with unprecedented compressive and tensile strength. Also, to overcome congestion caused by rebar, stronger rebar alloys with strengths of 75–100 ksi (thus taking up less volume) could be adopted. Thus, the future is expected to be characterized by significant increases in the strength as well as reductions in the sizes of concrete columns and shear walls and steel columns and trusses. Improvements in structural design and analysis will translate into new "geometric freedoms" and will encourage bolder structural and architectural designs involving the complex geometries of exterior and interior elements. Many forms of structural systems that are currently considered impossible or too expensive are expected to become the mainstream. The future of structural engineering will also be shaped by advancements in computers and information technology (Smoothwhirl, 2009) as multidimensional computer simulation and visualization become essential tools for the structural engineer for quickly and efficiently designing and evaluating bridges, tall buildings, and other large or complicated structural systems. In addition to these opportunities, threats loom on the horizon: Future developers of civil engineering structural systems also will need to contend with the impacts of climate change on their structures; namely, altered frequencies and intensities of extreme weather, climate, and sea levels will translate into a myriad of consequences, such as longer droughts, more frequent and severe freeze–thaw cycles, warming of ocean surfaces (resulting in more intense typhoons and hurricanes), larger and more abrupt floods, changing levels of groundwater, and changes in wind speed and profiles (Lenkei, 2007). These, in turn, will accelerate surface deterioration, low cycle fatigue, and accumulated damage, thereby fostering the need to review design codes for planned structures and to adopt adaptation and mitigation measures for existing structural systems (Long and Labi, 2011).

1.2.2 Transportation Systems Engineering

Transportation engineering can be described as the science of providing systems for moving people, goods, and services safely and cost-effectively by sea, land, or air (Fricker and Whitford, 2005). From the modal perspective, transportation engineering therefore has subbranches, such as highway engineering (roads), railroad engineering (freight rail), transit engineering (heavy rail, commuter rail, light rail, monorail, etc.), port engineering (harbors, canals, and other maritime facilities), pipeline engineering, and airport engineering. Other subbranches are typically associated with nonmotorized urban travel and include pedestrian and cyclist management.

For each mode, the functional areas include planning, design, and construction of the system, traffic operations and capacity management, congestion mitigation and safety management, and facility preservation. It can be observed that these functional areas follow a certain sequence or a life-cycle pattern, which we shall discuss further in Chapter 2. Thus, from the phasal perspective, the transportation engineering subbranches could be established also on the basis of the functional area. This explains why at many universities or public agencies, transportation departments are divided not only according to the mode involved (highway division, railway division, etc.) but also on the basis of functional area (planning division, design division, operations division, maintenance division, etc.).

The planning aspects of transportation engineering, for any mode, include facility location, demand assessment, cost estimation, and impact assessment in terms of air quality, mobility, safety, economic development, and other impact types. The traditional technique for forecasting demand is the four-step process: trip generation (how many trips are generated?), trip distribution (what are their destinations?), mode choice (which modes are used by the trip makers?), and traffic assignment (for each mode, what percentage of trip makers use each available route?). More sophisticated demand forecasting techniques consider other aspects of trip makers' backgrounds or the nature of their trips, such as auto ownership, residential or business locations, and trip chaining (linking separate trips together in a tour). Also, at the planning level, the expected system cost is roughly estimated using rules of thumb for other empirical models. Examples include average costs or cost models based on the aggregate characteristics of similar facilities built in the past, expressed per unit dimension or per unit usage such as \$/lane-mile or \$/passenger-mile, respectively, of the system.

In transportation system design for any mode, engineers determine the appropriate size, materials, orientation, and geometry of transportation facilities. These include the guideway (runway, railway, or highway pavement); terminal; intermediate; or nodal facilities for intermodal overlaps or intramodal directional exchanges or transitory repositories such as highway intersections, rail intersections, terminals, parking garages, and so on. At the design phase, costing is more detailed and yields a relatively more reliable estimate that is based on the cost buildup from the unit costs of the individual pay items of the materials, labor, and equipment used for each specific task. This cost is often used as the basis for bid evaluation.

At the operations phase of any transportation mode, transportation engineers establish optimal operational controls so that the delay or travel time for passengers or freight is minimized. Thus, traffic engineers in any mode develop guidance and information for its users through signs, signals, markings, and more recently newer intelligent transportation systems (ITS) technologies such as advanced traveler information systems (changeable message signs), commercial vehicle facilities [Global Postioning System (GPS)-enabled advisory systems], advanced traffic control systems (arterial signal coordination), and vehicle–infrastructure integration. Engineers strive for safe operations of their systems by including safety elements in their designs or by making continual recommendations for safer facility operations by analyzing crash patterns, frequencies, and severities at various links and nodes of each mode.

History of Transportation Systems. The need for transportation infrastructure arose from the gradual evolution of ancient societies from subsistence lifestyles to communities that produced and exchanged goods and services. The earliest transportation mode was land transport by way of earth tracks through forests and grasslands. First blazed by hunters as game trails, these tracks subsequently evolved into paths for humans and domesticated animals carrying goods to and from trading posts. Increases in trade volume led to widening or strengthening of the tracks to accommodate more frequent and heavier traffic. In this section, we discuss the evolution not only of civil infrastructure but also of the mechanical devices that complemented the use of these civil facilities. In ancient Sumeria, animal-powered wheeled vehicles were developed in 500–400 BC, and this technology spread to other parts of the world. Archeological evidence of this can be seen in areas of the Minoan cities in ancient Crete (2700–1450 BC) that were well connected with stone-paved roads formed using saw-cut blocks (Shuter, 2008). On the Indian subcontinent circa 4000 BC, the critical role of transportation infrastructure in the economy of the Harrapan and Mohenjo-daroor (the Indus Valley civilizations) is evidenced by archeological remnants of paved streets and land transport vehicles such as bullock carts (Carr, 2011). In pre-Columbian South America, several roads and trails, such as the 22,000-km Inca road network system (El Camino Inca) of Peru, were constructed to facilitate commerce, and Inca rope bridges provided access across valleys (Kirby, 1990).

While the origin of highways can be traced to prehistoric tracks and bronze-age ridgeways, it was only after the rise of strong centralized governments that complex road systems emerged (Needham et al., 2001). As empires expanded, the need to control conquered areas generated a large demand for accessibility and mobility through perennial road networks. Circa 300 BC, the Magadha Empire (in present-day India) under ruler Chandragupta Maurya was extended from the Arabian Sea to the Bay of Bengal, and extensive road networks were built to facilitate movement of its military, which was considered to be the largest army in the ancient world. Also during that era, the ancient Romans in the expansion of their empire, had great road engineers whose vocation was one that could ultimately lead them to occupy high (political) offices in the state. The Roman road system was a 50,000-mile network that included almost 30 military highway sections centered in Rome. Even today, their remnants can be seen in areas that were a part of the ancient Roman Empire, from Spain to Syria and from England and the Danube to North Africa. The greatest of the Roman roads was the 360-km-long and 14 Ft-wide Via Appia, or the Appian Way (Figure 1.6) named after

Figure 1.6 The Appian Way, an ancient Roman highway constructed in 312 BC, is still in use today (Courtesy of Paul Vlaar).

ruler Appius Claudius Caecus (Pannell, 1964). This highway, which was constructed with huge lava block paving in a bed of crushed stone cemented with lime, runs from Rome to Brindisi, and parts of it are still in use today. Also in the pre-Christian era, there existed road tunnels in Rome, such as the Petra Pertusa Tunnel on the Via Flaminia and the 2300-ft-long Grotta of Naples, which connected the city with the suburb of Bagnoli. Other civilizations, such as that of ancient Greece, were also known for impressive highway systems: the urban streets and market squares of ancient Greece were mostly paved, and in rocky areas, the roads consisted merely of two wheel ruts carved into the rock, resembling a rail track. Crossing points for vehicles driven in opposite directions were provided at certain intervals. However, the difficulty of letting other travelers pass often led to bitter disputes, the most famous being that between Oedipus and King Laius; and this quarrel led to the patricidal tragedy that was later documented in the journals of Sophocles, the Greek philosopher (Kirby et al., 1956). Another example of excellent highway systems of that era is the Persian Royal Road of the Achaemenid Empire built circa 500 BC by King Darius I (Needham et al., 2001). This highway stretched from the city of Sardis near Izmir (in present-day Turkey), passed through Nineveh, the Assyrian capital that is the site of the present-day city of Mosul in Iraq, and Babylon (near present-day Baghdad, Iraq) and split to join Susa (in present-day Iran) and the Achaemenid capital city of Persepolis (present-day city of Parsa in Iran). At the height of the Ottoman Empire (AD 16–17), many highways, such as the Aleppo (Syria) to Baghdad (Iraq) Road, were constructed, some of which were paved using tar residue derived from distillation of the petroleum obtained in the region's oil fields. In China, in the first two centuries AD, under a succession of emperors, extensive imperial highways were built along the coasts and rivers, using a pavement material and structure similar to what later became used and known in Europe as "water-bound macadam." Several of these roads (notably, including some sections of the link between the Chhin capital in the north and the Szechuan basin in the south) were constructed in straight lines, cut through mountains, and carried on embankments in valleys; erosion control material was provided for embankment slopes (Needham et al., 2001). The Pei-chan Lu (or North Trestle Road) linking Shu to Kuan-chung was aptly named for the massive pillars and beams that supported the road through the ravines it traversed.

In Europe in the 19th century, engineers John McAdam, John Metcalf, Robert Phillips, Thomas Telford, and Pierre Tresaguet made significant contributions to road science, including the use of pavement designs that incorporated self-draining surface slopes and carefully selected sizes of stone aggregate and soil. At the 19th to 20th century transition, advancements in land vehicles, from horse-drawn vehicles to bicycles and motors and electric vehicles, spawned the development of land transportation facilities, such as the provision of impermeable surfaces and systematic drainage facilities, thus reducing the inconveniences of dust and mud bogs. The invention of the stone crusher and steam roller in 1959 increased the speed and economy of road construction (Kirby et al., 1956). The installation of automatic traffic signal systems began in the United States and Europe in the 1920s, following the invention of the traffic light by Garrett Augustus Morgan. The 1920s and 1930s saw a dramatic improvement in highway geometric design, culminating in the construction of high mobility and limited access superhighways or expressways, and interchanges.

In the area of maritime transportation, the Stone Age was characterized by the use of natural harbors that served fishing canoes and boats. Subsequent developments in maritime transportation infrastructure were facilitated by the needs of war and increases in trade volumes. Circa 4000 BC, canals were developed to facilitate inland water transportation in the ancient city-state of Mesopotamia (Shuter, 2008). There is evidence that in Mediterranean ports, galleys (seagoing vessels propelled mainly by oars) were developed circa 3000 BC. Commerce by merchants from the present-day Persian Gulf regions of Bahrain and Failaka was facilitated by an extensive maritime

Figure 1.7 Transportation engineers strive to maximize mobility and accessibility while minimizing travel delay, cost, and environmental degradation (Courtesy of renaissance-downtowns.com).

trade network operating between the Mesopotamian and Harappan (Indus Valley) civilizations. The long-distance sea trade was made possible not only by innovations in sea vehicle technology, such as plank-built watercraft and sail material and design, but also with natural, shallow harbors located at river estuaries. To accommodate larger vessels, natural ports were used and artificial ones were developed through dredging and other earthmoving activities. The first canal system in the world was built circa 2600 BC during the Indus Valley civilization in present-day Pakistan and northern India; this is evidenced by the recent archeological discovery of a massive, dredged canal and a docking facility at the Indian coastal city of Lothal (located in the modern state of Gujarat), dating from 2400 BC (Carr, 2011). In the Mediterranean, where tideless coasts provided natural settings for water-based travel, the Phoenicians, in 1200 BC, developed the port of Sidon for the purpose of maritime trade. In 490 BC, the longest canal of that era, the 1770-km-long Grand Canal of China, was constructed to transport Emperor Yang Guang and his entourage between Beijing and Hangzhou. Also, the ancient Greeks and Romans were adept at harbor building. However, unlike the Greek harbors that were located at places with minimal disruption to the existing currents, land form, and other natural features, the Romans did not shy away from radical disruptions of natural conditions. This difference in design philosophies probably explains why many ancient Roman harbors today are silted up or have succumbed to the sea (Straub, 1964). In the Middle Ages, the start of the 13th century saw the phasing out of galleys and the advent of large ocean-faring ships. These included caravels (a small Spanish, Portuguese, or Arabic sailing vessel rigged on two or three masts), the treasure ship (a large wooden vessel commanded by Chinese Admiral Zheng in the early 15th century), and the man-o-war (an armed naval vessel developed in the late 15th century in the Mediterranean that was propelled primarily by sails). Also, canals were built in the Middle Ages in the Italian city of Venice and in the Netherlands to facilitate inland transportation. Examples include the 240-km-long Canal du Midi in France that was built in 1680. During the Industrial Revolution, the first steamships, and later diesel-powered ships, were developed, and inland canals were built in England and in the United States.

With regard to rail transport, there is archeological evidence that probably the first engineered railway was the Diolkos Wagonway (6 km in length) in Greece circa 600 BC, built to transport boats across the Isthmus of Corinth for several centuries. This railway consisted of grooves that were carved in limestone to serve as the track, and the wheeled wagons were powered by slaves and animals (Lewis, 2001b). After a long break, rail transportation infrastructure reappeared in Europe in 1550 in the form of crude wooden tracks. In the 18th century, the first "modern" railroad on the European continent was a horse-drawn railway established to transport coal between Budweis (in modern-day Czech Republic) to Linz (in Austria). In the 1760s, cast iron plates were used as rails but were replaced decades later by rolled wrought iron rails due to the efforts of British civil engineer William Jessop in Loughborough. In England, mechanized steam-powered rail transportation systems first appeared in the early 19th century. At the start of the 19th century, the first rail-guided steam locomotive was built and operated by engineer Richard Trevithick in Wales, but it proved to be a financially unsustainable venture and led to Trevithick's bankruptcy (Ellis, 1968). With the development of railway systems in Great Britain in the early half of the 19th century, which included contributions by James Watt and George Stephenson, railway transportation gradually spread throughout the world and dominated long distance land transport for nearly a century (Ellis, 1968). This was before other transportation modes (air and highways) became viable or more cost-effective due to inventions in the vehicles used in those modes. In the United States, early railroads differed by their purpose and power sources. These included New York's gravity railroad in (1764), Pennsylvania's Leiper Railroad in (1810), Massachusetts' Granite Railroad in (1826), and the Baltimore and Ohio Railroads (1830). At the close of the 19th century, the development of diesel and electrical energy to replace steam as a rail power source was facilitated by developments in diesel and electrical technology. For example, the development of the pantograph by individuals, such as Granville Woods, and later adopted by engineering companies, including the Baltimore and Ohio Railroads and Siemens & Halske, enabled the conduction of electricity from overhead wires to railcars and led to the operation of the first electric rail system at Coney Island in New York in 1892. Thanks to developments in engine and guideway technology, the 20th century saw yet another generation of rail transportation: Japan's Shinkansen, France's *train à grande vitesse* (TGV), and Western Europe's Eurostar, and magnetically levitated trains (Maglev) in Germany, Japan, and recently China (Osorio and Osorio, 2006).

Air transportation, unlike the other modes, has a history characterized by watersheds that occurred mostly in the last millennium. However, the fascination of transporting people and goods by air dates back several thousand years when catapults were used in warfare and when humans desired to replicate avian flight as in the legends of Daedalus and Icarus in Greek mythology and the Vimanas in Indian mythology. According to engineering historians, the first attempts at flight were probably made in the 6th century in China by Yuan Huangtou who used a kite and Abbas Ibn Firnas in Spain who used a parachute and a controllable glider; in the 17th century, in Turkey, Hezarfen Celebi used a winged glider and Lagari Çelebi used a gunpowder-powered rocket for one-man flights (Darling, 2003). Then in 1783, the Montgolfier brothers in Paris developed hot air balloons for manned flight; and a year afterward, Jean-Pierre Blanchard, seeking to overcome the wind direction limitations of balloons, operated the first human-powered dirigible (NASA, 2002). Some of the notable dirigible developments that subsequently followed were Henri Giffard's machine-powered propulsion in 1852, David Schwarz's rigid dirigible frames in 1896, and Alberto Santos-Dumont's improvements in dirigible speed and maneuverability in 1901. Powered heavier-than-air flight, which was started by the Wright brothers in the United States in 1903, was subsequently enhanced with developments in flight control that made them practical for warfare and ultimately for transporting passengers and goods. Meanwhile, airships were used for a while to transport goods and passengers over great distances but saw sharply diminished use after 1937. The first, second, and third decades of the 20th century saw tremendous advancements in air transportation, and passenger airline service was started during this period as well. World War II was accompanied by several significant innovations in aviation including the first liquid-propelled rockets and the first jet aircraft. The end of the war was marked by a boom in general aviation. At the current time, air transportation is dominated by jet-powered aircraft developed in the mid-20th century.

By the end of World War II, highway engineering had begun to be recognized as a distinct area of engineering (this later evolved into transportation engineering, thereby covering the different modes of travel). Over time, it has been infused with techniques from economics, finance, materials science, and operations research. Important contributions in transportation engineering over the past 100 years include innovations in highway materials by Roy Crum and Prevost Hubbard in the 1920s, development of financial practices for highway engineering systems by Wilfred Owen in 1940, and establishment of relationships between guideway surfaces and operating costs in 1943 by Ralph Moyer. After World War II, there were important contributions as well, such as quantification of the influence of materials on pavement performance in 1946 by a team led by Kenneth Woods; innovations in concrete science by Charles Scholer in 1948; development of techniques for estimating the capacity of multilane highways by O. K. Normann; and pavement design improvements by F. N. Hveem and R. M. Carmany in 1949. Advancements in the 1950s included an analysis of accidents for highway planning purposes in 1950 by Roy Jorgensen and Robert Mitchell; development of the BPR function by Albert Goldbeck for traffic network studies; and technical and financial planning of interstate systems by Herbert Fairbank. Other enhancements in the 1950s included Burton Marsh's work on traffic safety, Ralph Moyer's contributions to urban transportation systems planning, and Tilton Shelburne's research in highway skid analysis. Also in that era, notable contributors to highway engineering systems included Harmer Davis for his research in transportation efficiencies, Guilford St. Clair for transportation finance, Merlin Spangler and Robert Litehiser for highway drainage, and Alan M. Voorhees for identifying patterns in urban travel. The 1960s continued the trend of innovations in materials and a continuation of the innovations in the emerging science of transportation operations. This work included William Goetz in bituminous materials and Bryant Mather and Fred Burggraf in concrete technology and science, as well as Alvin Benkelman who was the inventor of the Benkelman beam device for measuring road surface deflection, and Francis Turner who uncovered patterns in urban transportation system operations.

The Future of Transportation Engineering Systems. As we move deeper into the new millennium, the transportation engineer will be faced with a variety of challenges that will require more explicit adoption of "systems" concepts and approaches for their resolution. Some of these developments include increased population and travel demands that lead to traffic congestion and air pollution in urban areas and increased need for accessibility by rural populations in developing countries; aging transportation facilities, many of which were built several decades ago and have surpassed their design lives; the incorporation of several stakeholders in transportation decision-making processes and higher user expectations; increased threat of terrorist attacks on transportation systems, vulnerability to natural disasters, transportation system resilience to hazards, and postdisaster recovery; and, finally, tightened funding to maintain, rehabilitate, and reconstruct aging transportation infrastructure. Other ongoing and emerging issues to be faced by transportation engineers of the future include sustainability of transportation systems from the perspectives of the environment, safety, sociocultural impacts, land use, energy use, and climate change (Sinha, 2003). At a tactical level, engineers will exploit new technologies for real-time monitoring and optimizing of transportation system operations. Transportation infrastructure engineers will also seek to enable real-time inspection and monitoring of the physical condition and usage patterns of systems to facilitate timely and cost-effective interventions that preserve the system physical and operational integrity. Furthermore, major advances in intelligent transportation systems (e.g., information and communication technologies) and innovations in building materials, nanotechnology, and vehicle technologies (e.g., propulsion and new fuels) are expected to open up new horizons in transportation engineering through increased opportunities for cost reduction, greater mobility, enhanced safety and security, and increased system longevity and economic productivity.

1.2.3 Hydrology and Hydraulic Systems Engineering

Hydrologic systems engineers analyze the occurrence and distribution of water in the air, land, and sea. Their central theme is the cyclical movement of water throughout the Earth through different pathways. These pathways are characterized by the evaporation of water from oceans to form clouds; precipitation in clouds as rain or snow; flow of rainwater (runoff) across land surfaces into rivers, streams, and lakes; in-ground percolation of water into lakes, rivers, or aquifers; return of water to the atmosphere through evaporation from the surfaces of water bodies or through plant transpiration to the atmosphere; and precipitation from the atmosphere and surface water discharge into the ocean. The subbranches of hydrology include hydrogeology (study of the movement of water in subsurface bodies including aquifers), hydrometeorology (study of water and energy transfers between the atmosphere and surfaces of land and water bodies), and surface hydrology (study of hydrologic processes that occur at or near the Earth's surface), and hydroinformatics (the adaptation of computer information technology to hydrology and water resources applications).

Hydraulic system engineers study the mechanical properties of liquids, including energy exchanges due to fluid flow. They also analyze the properties of fluids in motion and the interactions between a flowing fluid and its immediate environment (Lyn, 2004). These engineers plan, design, and manage engineering structures for water supply and distribution and also to control water flow, such as dams, water-crossing bridges, levees, networks for water supply and distribution, urban drainage systems, channels, and transportation canals. Figure 1.8*a* shows the Falkirk wheel, a rotating hydraulic boat lift that connects the Union Canal and the Forth and Clyde Canal in central Scotland. Hydraulic engineers manage irrigation, flood and erosion control, and coastal protection. Hydraulic systems play a critical role in society's need for water conservation, flood control, and drainage. In the recent era that is characterized by wild fluctuations in weather patterns induced by climate change, it has become important to protect facilities located near the coast, lakes, or large rivers from inundation using dikes, sea defense walls, coastal barriers, levees, and other hydraulic systems. Figure 1.8*b* shows a coastal defense barrier at the Isle of Wight in the United Kingdom.

History of Hydrology and Hydraulics. Throughout the ages, proximity to freshwater sources has always served as a main catalyst for human settlement and development. Most major cities in the world are located along the banks of a river. Proximity to water, however, is a double-edged sword: Engineers harness this resource for purposes of irrigation and water supply but also need to protect human settlements from inundation during flood events. The expansion of population and the development of trade over the millennia has led to the increased importance of water for agriculture, water supply, and transportation. As far back as 4000 BC, the Nile River was dammed to enhance the fertility of surrounding land. Also, in the ancient city of Babylon located in the desert empire of Mesopotamia (circa 1760 BC), water resource management was so vital to the empire's socioeconomic fabric that a large system of irrigation canals was constructed and special officials were appointed to supervise the operations of these engineering systems. The officials ensured that the canals were clear of debris, weeds, and silt in order to prevent flooding. The ruler, King Hammurabi, through his provincial governors, personally directed the excavation and dredging of the

(*a*)

(*b*)

Figure 1.8 (*a*) Hydraulic-lift wheel, Falkirk, Scotland and (*b*) coastal defense structure in operation [Courtesy of (*a*) AndiW/Wiki Commons and (*b*) Oikos-team at en.wikipedia].

canals on a regular basis and the construction of high earthen walls near townships to protect them from floods. Also, to prevent neglect of the canals, the king established a set of common laws (probably the world's first), which included clauses that addressed the construction of these and other structures. These clauses struck terror in the hearts of unethical contractors as Hammurabi's strict code of justice dealt a heavy hand to incompetent builders. Those whose structures collapsed and resulted in the deaths of people faced a sentence of death (Prince, 1904). In the Indus Valley civilization era (3000–1500 BC), the hydraulic engineering skills of the Harappans were evident in their documented academic study of tides, waves, and currents and in their dock building (Carr, 2011).

Other hydraulic systems that were designed and constructed before or during these eras include retention basins, canals, irrigation ditches, and dikes in various parts of the world. In ancient Egypt, drinking water was transported to the city of Memphis in 3000 BC, a channel was built to connect the Red Sea and the Nile River in 1950 BC, wells exceeding 300 ft in depth were dug in 1700 BC, and water tunnels in hills were constructed in 1200 BC as part of war preparations (Biswas, 1970). In approximately 600 BC, China's first recognized hydraulic engineer, Sunshu Ao, rose to political prominence in the State of Chu due to his engineering skills, and he ultimately was appointed prime minister. For purposes of irrigation and water supply, Ao constructed the Shao Bei Dam in the Northern Anhui Province and created the Anfeng Tang Reservoir System that is in operation even today (Needham, 1986). Another hydraulic engineer of that era, Ximen Bao, circa 400 BC, diverted the Zhang River from flowing into the Huang He River near Anyang and established a different course that met the Huang He further downstream near the modern-day city of Tianjin. He also created a large canal irrigation system for the agricultural region of Henei.

In the Neo-Babylon Empire under Chaldean rule, circa 700–500 BC, there were significant advances in the engineering of hydraulic structures. One of the earliest aqueducts on record has been attributed to the Assyrian master builder and ruler Sennacherib (circa 700–680 BC) who governed with “a heart of wrath” and exploited the power of water equivocally: During times of peace, he harnessed water bodies to develop the capital city of Ninevah and his Khorsbad palace; and in times of war, he unleashed water as a weapon to flood and destroy enemy strongholds. Sennacherib used 18 freshwater courses from the mountains, 2 dams, and a 3-stage 10-mile-long water canal to develop a sophisticated water supply and distribution system. Water was also transported using an aqueduct reinforced with hardened clay and waterproofed with bitumen. The aqueduct, which ensured a continuous supply of water to the city, crossed valleys on arched bridges.

Ancient Greek philosophers had pondered various aspects of what is now known as the hydrologic cycle. Tartarius (400 BC) suggested that a large underground sea existed that replenished the oceans, and a century later Theophroastus published the first meteorological abstracts (Leonard, 2001). In ancient Rome, Frontinus, a famous engineer who managed the aqueduct systems in that era, authored *De aquaeductu*, an official report to the emperor on the state of Rome’s water supply system, including the laws relating to its use and maintenance.

The aqueducts were built by the ancient Greeks and Romans transported water over long distances. Also, in ancient China, remarkable hydraulic systems including canals and irrigation channels were used to harness water for transportation and agriculture purposes for thousands of years (Needham et al., 2001): Dujiangyan, a massive irrigation system involving the Minjiang River in Sichuan, China, was built in 250 BC and is still in use today; also, in the Chin and Han dynasties, great efforts were made to conserve freshwater resources through dike strengthening and other activities under great engineers such as Chia Jang in AD 6. The 1770-km-long Grand Canal of China, which connects Beijing in northern China to Hangzhou in the south (Pannell, 1964), commenced construction in 5 BC. The construction of the Chengkuo Irrigation Canal, the Kuanhsien Irrigation System, the Ling Chhu Transportation Canal, and the Chhien-thang Sea Wall are evidence of the great skills of hydraulic engineers at the time. Interestingly, there existed two rival philosophies that influenced the design of hydraulic systems in China: The Taoist philosophy of greater freedom for natural courses advocated the use of “feminine” activities, such as dredged concavities; and the Confucius philosophy of confining and repressing nature advocated “masculine” activities, such as dike construction. This is similar to the dichotomy between the ancient Greek and Roman philosophies of civil engineering. At the time of the legendary Emperor Yao, his engineer Kun adopted the masculine approach and built several dikes but failed to stem the water flow and ultimately suffered punishment through exile and execution by the emperor. Kun’s son, Yu, who adopted the feminine philosophy, was more successful in controlling the floodwaters. The first use of pound locks was by the Chinese several centuries later at the beginning of the Sung dynasty, by Chhaio Wei-Lo, assistant commissioner of transport in Huainan City circa AD 1000.

In the 3rd century BC, Archimedes invented a hydraulic system consisting of a screw, a helical surface surrounding a central cylindrical shaft installed inside a hollow tube (Figure 1.9). When the screw is turned, the bottom end scoops up an amount of water, which slides up in the spiral tube until it finally pours out from the top end of the tube. This innovation was used to draw water from

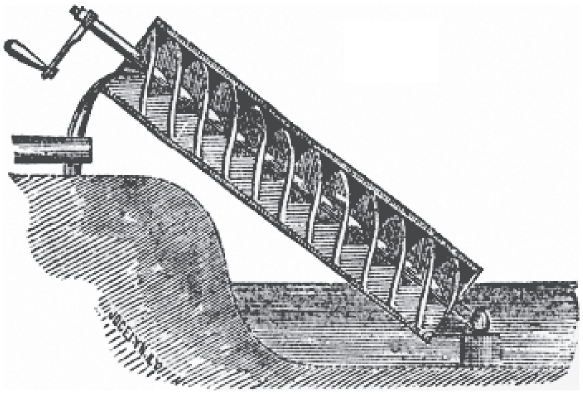


Figure 1.9 Archimedes' screw (Courtesy of Ianmacm at en.wikipedia).

low-lying areas or flooded mines in order to drain those areas or to lift water to higher ground for irrigation purposes.

In ancient India, the era of the Mauryas was characterized by significant hydraulic engineering works including dams and canals. In the 11th century, significant hydraulic systems included the 250-square-mile artificial Bhojpur Lake and the 16-mile Jayamkonda Dam, constructed under the Bhoja and Chola Dynasties, respectively. In ancient Rome in the first century BC, Marcus (Vitruvius) Pollio, an engineer, described a philosophical theory of the hydrologic cycle, in which precipitation fell on the land, infiltrated the earth's surface, and recharged underground streams and water bodies or run-off from the land surface as streams and springs. The Etruscans and Romans were masters of constructing water supply and drainage systems. An example is the draining of Lake Fucino, a drainage project in Italy in AD 45 where a 3.5-mile tunnel and 28-ft drop were constructed through the mountains of Salviano to provide an escape run-off for the trapped lake, a feat that evidenced great skills not only in hydraulic engineering but also in construction engineering and surveying. In the last three centuries BC, the Romans constructed a magnificent system of aqueducts; and under Emperor Tiberious, these systems provided an astonishing 180 million gallons of freshwater for Rome. In AD 97, Julius Sextus Friontius, given responsibility by Emperor Nerva for the water supply of Rome, personally inspected the existing aqueduct system and documented the designs and operational procedures of that system (Landels, 1978).

The Pont du Gard Aqueduct in southern France transported water across the small Gardon River Valley, the aqueduct helped deliver approximately 5 million gallons (20,000 m^3) of water daily from the Uzès Springs to the ancient Roman city of Nemausus (present-day Nimes). At its first level, the aqueduct carries a road. Also, the ancient Sinhalese (circa AD 300–500) utilized concepts of hydrology to build remarkable irrigation systems, large water reservoirs, dams, and water canals, some of which are in use in present-day Sri Lanka. They are also known for having invented a number of hydraulic devices, such as anicut stones and removable pillars, to facilitate water intake, control water flow, or prevent erosion. Also, circa AD 200–600, during the Sassanid era in the Middle East (the last pre-Islamic Persian Empire), the 250-mile Nahwawan Canal was constructed to improve the management of the region's water resources (Needham et al., 2001).

Leonardo da Vinci established the relationships between channel area, water velocity, and flow; and his paper "Treatise on Water" explained the origin of lakes and rivers, water evaporation and condensation, open-channel flow theory, and the relationship between hydraulic head and flow. Subsequent work by da Vinci and Bernard Palissy in the 15th century separately yielded more accurate representations of the hydrologic cycle. In 1598, Giovan Fontana established the link between velocity and discharge; and in 1694, Pierre Perrault established relationships between rainfall intensity and resulting surface flow using his observations of the Seine River. Other pioneers of the modern science of hydrology in the 17th and 18th centuries include Edme Mariotte, who carried out measurements of water velocity and river cross section to determine the relationships between these variables and water flow, and Edmund Halley, who demonstrated that the water evaporation from the Mediterranean Sea surface adequately accounted for the outflow of surface water bodies flowing into that sea.

In the field of hydraulics, Vitruvius, a few decades BC, documented techniques for aqueduct construction and the use of the inverted siphon. During the Renaissance period in Europe, renewed interest in scientific thought spurred advancements in hydraulic science (Biswas, 1970). With regard to water supply systems, probably the greatest breakthrough was the invention of the cast iron pipe in the 17th century, which enabled the conveyance of water under great pressures (Leonard, 2001). The 18th century saw advances in hydraulics that included Daniel Bernoulli's piezometer and the Pitot tube invented in the early 1700s by Henri Pitot, an Italian-born French engineer. Pitot disproved the then commonly accepted notion that at greater depth, the speed of water is greater. In the 1900s, there were further developments in groundwater hydrology and hydraulics, including Darcy's law, which shows how fluids flow through porous media; the Dupuit–Thiem formula, which described underground water flow; and Hagen–Poiseuille's equation, which explained capillary flow patterns. In the 20th century, rational analyses began to replace empiricism, and important contributions were made by Leroy Sherman (the hydrograph), Robert Horton (infiltration theory), and C. V. Theis (aquifer test and equation governing well hydraulics). The 20th and 21st centuries also have been characterized by approaches that are increasingly theoretical in nature, a trend that has been facilitated by increased recent understanding of hydrological processes and also by the advent of computational, mapping, and visualization capabilities such as Geographic Information Systems (GIS).

The timeline for the development of the science of hydrology can be presented into eight-periods (Chow, 1964; Rao, 2002) as shown in Figure 1.10: The *speculation period* when conjectural speculations were rife regarding the different aspects of the hydrologic cycle, and practical knowledge of hydrology was used as a basis for hydraulic structure construction; the *observation period* when hydrological variables received close observation and scrutiny by scientists who had an understanding of the hydrological cycle including Bernard Palissy and Leonardo da Vinci; the *period of measurement* when scientists started measuring hydrologic variables and the science of hydrology was born; the *experimentation period* that laid the building blocks for modern hydrology; the *period of modernization*; the *period of empiricism* when hydrological knowledge was mostly based on empirical observation; the *rationalization period* during which scientists made theoretical contributions relating to the hydrograph, infiltration, and groundwater processes; and the present period called the *theorization period* characterized by the use of information technology to develop and validate complex theories.

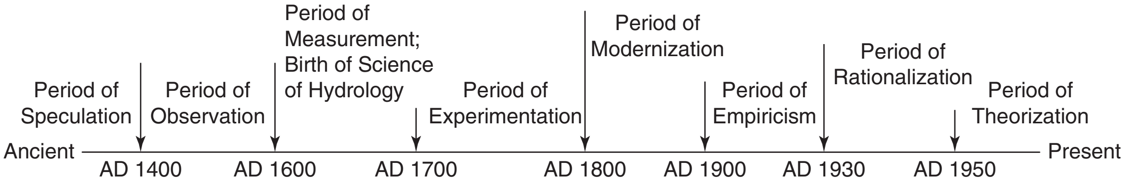


Figure 1.10 Development of hydrology—timeline.

The Future of Hydrologic and Hydraulic Engineering. As we enter the new millennium, the two-way relationships between water resource systems and socioeconomic development will become increasingly visible and important. These impacts will be driven by political and economic uncertainties, increases in world population, and anthropogeny-driven climate changes (Delleur, 2003). Global warming is also expected to lead to rising sea levels and greater volumes of surface runoff, which will necessitate new designs and performance reviews of existing hydraulic systems. In the future, it is also expected that there will be advances in the tools used in analyzing hydrologic and hydraulic systems, including remote sensing, GIS, and hydroinformatics (the application of databases, software, and expert systems). Continuing advancements in the fields of mathematics and computer science will enable future hydraulic engineers to enhance hydroinformatics to encapsulate existing knowledge through genetic programming, data mining, and artificial neural networks for a variety of tasks, including real-time control of urban drainage systems (Abbot et al., 2001). Since the 1993 major flood events in the Mississippi and Missouri basins, the traditional approach of designing the water resource system first and then considering the impacts is gradually giving way to a systems approach in which the hydraulic, environmental, and ecological aspects are all included simultaneously in the planning, design, construction, and operation of such systems (Starosolki, 1991). This trend is expected to continue in the future. Hydraulic engineers will continue to focus on environmental issues, sustainability, and management; and they will seek and utilize more effective ways to engage stakeholders and society in general in their decision-making processes (Chanson, 2007). Furthermore, because of the multiplicity of water sources, the variability of response times in the hydrologic cycle of each source type, and the myriad of current and future uses of water, planners, designers, and operators of hydraulic systems will be expected to deal with a multitude of ongoing and emerging problems associated with physical management of water resources, such as identification of new sources of freshwater, cost-effective water supplies, flows in water bodies, flood protection, hydropower generation, and water transportation.

1.2.4 Environmental Systems Engineering

Environmental systems engineers apply scientific and engineering principles to enhance the quality of the environment (land, air, and water) so that it is healthy for the humans, flora, and fauna that inhabit it, which includes prevention of pollution as well as remediation of polluted areas. Pollutants may be chemical, biological, thermal, radioactive, or even mechanical. The erstwhile terms "sanitary engineering" or "sanitation engineering" are more aligned with public health engineering and thus have a scope that is narrower than environmental engineering. Perhaps the most cross-disciplinary of all civil engineering fields, environmental engineering incorporates physics, mathematics, chemistry, biology, ecology, geology, law, and public health. Environmental engineers are responsible for or involved in recycling, waste disposal, environmental impact assessment and mitigation, water treatment and supply wastewater conveyance and treatment (Figure 1.11), and management of solid or hazardous waste.

History of Environmental Engineering. Historical records suggest that, throughout the ages, people have appreciated the direct relationship between their health and the quality of their environment and thus have sought to apply scientific and engineering concepts to enhance their environments. These applications include the generation and distribution of drinking water and proper disposal of wastewater. Scholars have credited the Sumerians in Mesopotamia, the Minoans in Crete, the Harrapans in the Indus Valley, and the Egyptians for developing early technologies that enhanced environmental quality in those eras. Engineering historians have observed the parallels

Figure 1.11 Digesters at the wastewater treatment plant Deer Island, MA (*Source:* Frank Hebbert/Wiki Commons).

that run across these civilizations: high population density, proximity to major rivers, fluctuations in river levels, and high summer temperatures (Leonard, 2001).

There is archeological evidence that King Menes in ancient Egypt developed water supply and distribution systems that were critical in sustaining that civilization. In ancient Greece, there were elaborate systems for water supply, wastewater discharge, and water transportation. On the Mediterranean island of Crete, the palace of Minos in the Minoan civilization (3400–1200 BC) had latrines outside of residences, stone-constructed systems for drainage, and pressurized systems for water supply (Buescher, 2000). Other environmental engineering feats of the ancient Minoan people of Crete (3000–1500 BC) included detailed systems for storm drainage and disposal of sewage that bear similarities to those of today. The Minoan city streets had water draining facilities, and clay-piped sewer facilities were available to the upper-class citizenry (vestiges of these pipes still carry runoff from heavy rains today). Sewers fitted with ventilating shafts were located beneath certain streets that collected liquid waste from residences. Also, circa 3000–1500 BC, cities in the ancient Harappan civilization, which were located in present-day India, Pakistan, Afghanistan, Turkmenistan, and Iran, filtered their water with charcoal and treated their water with copper containers that helped kill disease-causing germs. They also had a detailed system for draining storm water and residential wastewater as part of their overall city planning, as evidenced by archeological excavations at the city of Mohenjodaro.

Ancient Romans constructed aqueducts to transport water over long distances in a bid to prevent drought and to establish a consistent and healthful supply of water for residents, often using water treatment techniques such as filtration through porous vessels and water treatment by adding chalk and aluminous soil (Leonard, 2001). In ancient Rome, the main sewer, the Cloaca Maxima, not only drained a number of marshes in the valleys but also collected and drained human waste and storm runoff into the Tiber River (Lanciani, 1967). The ancient Greeks sought to protect their water systems from their enemies by laying their aqueducts underground, sometimes to a depth of 60 ft, and the deeper ones were connected to the surface through large wells. For treating their wastewater, the ancient Greeks constructed tri-compartment cisterns to help settlement of the wastewater (Leonard, 2001), a concept similar to present-day septic tanks.

There seems to be little evidence that the engineering knowledge displayed by the Romans was passed on to successive civilizations after the fall of that empire. In medieval Europe, there seems to be very little development of environmental sanitation or water infrastructure in the cities. As such, outbreaks and epidemics of infections and plagues among the dense populations were quite common.

Governmental intervention has been more widespread in environmental engineering than in any other branch of civil engineering. Throughout history, there have been acts of legislation that regulated public actions (and inactions) that could potentially harm the environment, ranging from edicts by the ruler of Babylonia circa 1890 BC, for city inhabitants to desist from actions that tended to clog the canals to laws passed by parliaments in European countries in the 19th century and legislation passed in the United States to restrict water and air pollution in urban areas. Laws were passed in the 15th century in Bavaria, Germany, to reduce the rate of alpine forest degradation, thereby helping to protect the quantity and quality of water supply in the region. In the Middle Ages in London, it took the passage of legislation to help improve the sanitary situation, for example, the Bill of Sewers and other laws were passed in London to regulate the discharge of storm water from gutters and liquid waste from residences; and in 1843, laws were passed in Germany to require the construction of sewers in certain urban areas (Leonard, 2001). In Europe during the Middle Ages, many city inhabitants simply threw their household human waste out the window (Rayburn, 1989) causing aesthetic problems and health hazards. Engineers in London in the mid-19th century proved that provision of good drinking water and effective disposal of wastewater could drastically reduce the incidence of waterborne diseases such as cholera and that additional laws were needed to enhance the city's sanitation.

In 1727, Sir Francis Bacon documented his experiments in water treatment techniques such as boiling, distillation, percolation, and clarification; some of his work is being used in modern-day environmental engineering (Baker and Taras, 1981). A watershed in clean water supply was marked in the United States in 1840 when the 41-mile Croton Aqueduct was constructed in New York City to deliver 95 million gallons of water daily to Manhattan (Leonard, 2001). The Lawrence Experiment Station also was commissioned in Massachusetts to carry out research into wastewater treatment processes. In the 19th and 20th centuries, prominent environmental engineers included Thomas Crapper, who invented the flush toilet; Paul Roberts, who applied the fundamental principles of chemistry and mass transport to water and wastewater treatment and wastewater reclamation; and Abel Wolman, who introduced the field of sanitary engineering and standardized the methods used to chlorinate drinking water supplies. In the 20th century, cesspools were replaced by sewers in most cities, and the processes of water treatment significantly improved, particularly due to disinfection via filtration and chlorination (Marhaba, 2000). For example, chemical coagulation process was first used in 1904 at a municipal water supply system (the Chain of Rocks Purification Plant in Missouri), activated sludge plants were implemented through pilot schemes in New Braunfels and Houston, and full operations began in 1926 at Milwaukee's Sewage Treatment Plant.

The Future of Environmental Engineering. As the world population continues to grow, greater demand is being placed on the quality of the Earth's natural resources and environment. Treatment and disposal methods that were once adequate now require far greater levels of cleanup before discharge into the natural environment (air, land, and surface and ground waters). These substrates are no longer considered free economic goods as has been assumed for decades; that is, their consumption generates to society, a cost that can be measured as the cost of avoiding their contamination or the cost of remediation (Jacko, 2003). In developing countries, the availability of clean drinking water will continue to pose a challenge for governments, and millions will likely die annually from unsanitary water-related conditions unless drastic steps are taken (Leonard, 2001). In developed countries, environmental engineers will continue to wrestle with problems related to anthropogenic air pollution, water resource degradation, ecological damage, and possible contamination from hazardous waste disposal. The role of the environmental engineer will be expanded to explain and mitigate the incidence of pollution-related diseases. Increasing realization of the unsustainable practice of nonrenewable fuel use will spur environmental engineers to play a growing advisory role in the global search for alternative energy sources. As we move into the new millennium, environmental engineering will be increasingly characterized by the application of new sustainable technologies to address these persistent problems. The emerging field of environmental biotechnology is expected to expand to help in pollution detection, remediation, and prevention.

1.2.5 Geotechnical Systems Engineering

Geotechnical engineers study the mechanical behavior of earth materials and, specifically, the state of rest or motion of soil bodies under the action of force systems (Harr, 2004). Geotechnical engineers use the principles of soil mechanics and rock mechanics to carry out at least six general activities: investigate and monitor subsurface conditions and surficial materials at a site, ascertain the relevant geotechnical properties of the site materials, evaluate and monitor the geotechnical integrity of manmade or natural soil/rock slopes and deposits, assess and monitor the risks associated with site conditions, carry out earthwork and structure foundation designs and monitor the geotechnical performance of these designs, and prescribe ground improvements to enhance the geotechnical integrity of a site (Holtz and Kovacs, 1981; Terzaghi et al., 1996).

Geotechnical engineers perform site investigations (surface and subsurface exploration) and laboratory tests in order to acquire information about the mechanical and chemical properties of a site's subsurface characteristics and thus carry out more reliable geotechnical assessments of the site. In such investigations, the site's underlying and surficial soils and bedrock are characterized; then the geotechnical integrity of the site is assessed on the basis of how the underlying soils will behave in response to loading from the proposed structure. Geologic mapping, photogrammetry, and satellite maps are used to obtain additional subsurface data at the sites. This is often supplemented by geophysical techniques such as seismic waves and electromagnetic surveys (including resistivity, magnetometer, and ground-penetrating radar (GPR)). Subsurface exploration usually involves direct soil testing at the site (Figure 1.12*a*) and laboratory tests on the samples retrieved from the site (Figure 1.12*b*). Geotechnical field tests include trial pitting, boring, drilling (small-diameter boring), trenching, cone penetration testing (CPT), and trenching (particularly for locating seismic faults). Large-diameter borings enable direct visual examination of the in situ soil and rock profile, but this technique is used only when it is safe and relatively inexpensive to do so. The engineer examines the soil or rock cuttings expelled from the drill hole during drilling operations, retrieves soil or rock samples at various depths from the drill shafts, and performs tests on the recovered soil or rock. For cone penetration tests, an instrumented probe with a conical tip is used, which is pushed into the soil manually or hydraulically and the rate of penetration is correlated to the soil properties. The dynamic cone penetrometer test (DCPT) is a popular test used to determine the strength of soil intended as subgrades for highway and airport pavement construction.

Geotechnical engineers also assess any risks associated with the site characteristics. Natural hazards include erosion, earthquakes, soil liquefaction, landslides, rock falls, and sinkholes. The risk assessment includes not only the vulnerabilities of the geotechnical system to the natural or built-up environment (including the structure, property, and humans) but also vice versa: the potential geotechnical hazards posed by the proposed structure to the natural or built-up environment.

Another key aspect of geotechnical engineering is the planning, design, and monitoring of earthwork, foundations, and other geotechnical systems for proposed structures or for repair of

(*a*)

(*b*)

Figure 1.12 Site and laboratory geotechnical tests help ascertain the integrity of underlying soils for construction. (*a*) Field sampling (*Source*: www.prlog.org) and (*b*) laboratory tests.

defective or distressed structures and earthworks due to adverse subsurface conditions. Geotechnical engineers develop site-specific foundation design recommendations and criteria for buildings, bridges, and highways. These designs include shallow foundations (footings and slab foundations), deep foundations (piles and drilled piers), lateral structures for earth support (cantilever walls, gravity walls, excavation shoring, and sheet piling), engineered slopes, geosynthetics, and earth structures. Earth structures include embankments, natural channels, dikes, pavements, reservoirs, tunnels, levees, and landfills.

In order to improve a site's geotechnical conditions, engineers often carry out ground improvement by modifying the properties (e.g., permeability, stiffness, and shear strength) of the existing ground. Ground improvement provides support slopes and foundations for several types of civil engineering structures and can reduce construction cost and time (Raju, 2010).

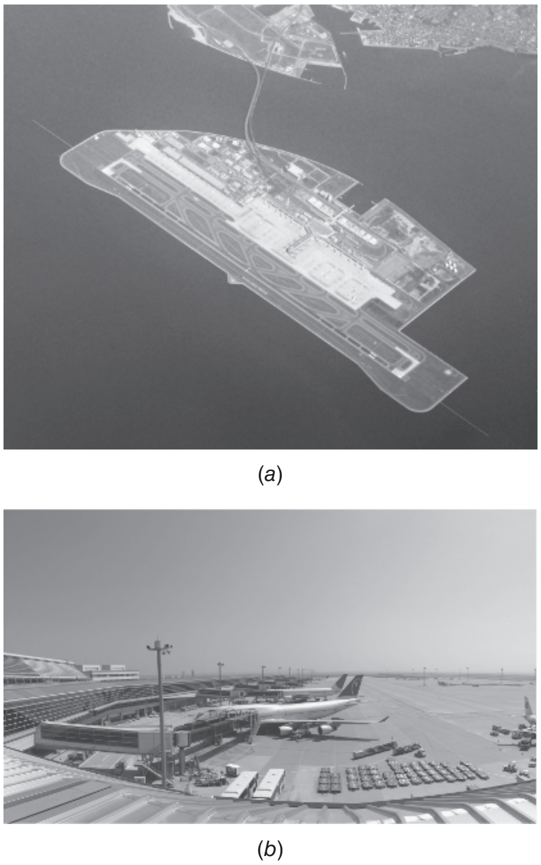
History of Geotechnical Engineering. Throughout the course of human history, soil and rocks have been used as material for various civil engineering and architectural purposes, including building foundations, burial sites, road construction, irrigation, and flood control. Soils of a specific nature were selected for constructing flood control structures in the ancient civilizations of Mesopotamia. Also, during the Indus River civilization (circa 2200 BC), earthen dikes were constructed along the Indus River to prevent flooding. For their temples and other structures, ancient Greeks and Romans used a variety of foundation supports, including strip-and-raft and pad footings.

For many centuries, the field of geotechnical engineering remained more of an art than a science and practitioners used past experience and trial and error. In the 18th century, after a spate of foundation-related engineering problems, scientists begun to seek more scientific approaches to designing foundations and making earthwork recommendations. Classical geotechnical science began in the late 18th century when Charles Coulomb introduced the concepts of engineering mechanics to the analysis and solution of soil problems. Other contributions during this period included Henry Darcy's work on hydraulic conductivity, Joseph Boussinesq's stress distribution theory, Christian Otto Mohr's theory of a two-dimensional stress state, William Rankine's work on the pressure theory, and Albert Atterberg's establishment of metrics to assess soil consistency.

Rapid population growth and increased rural–urban migration in the mid-19th century led to increased demand for taller buildings, extensive transportation systems, and construction of structures at areas hitherto deemed unsuitable due to relatively poor subsoil conditions. At that time, however, building foundation design and construction had advanced very little beyond those of the previous centuries. By 1879, however, critical geotechnical concepts had been developed, such as allowable bearing pressure, concrete and steel spread footings, and the steam pile hammer. As building heights increased due to increased land costs, availability of steel, and the invention of the elevator, the use of deep foundations gained popularity (Parkhill, 1998).

Modern-day geotechnical engineering was born in 1925 with the publication of *Magnum Opus, Erdbaumechanik* by Karl von Terzaghi. Other pioneers in the field included Arthur Casagrande (1902–1981), well known for his ingenious designs of soil testing apparatus and research on seepage and soil liquefaction. Despite the difficult economic conditions of the post-1930s era, federal spending on infrastructure projects helped support research by Terzaghi, Cassagrande, and other engineers. Technological advances that have spurred the development of soil improvement techniques included vibroflotation, vertical sand drains, wick drains, and rubber-tired roller compactors.

The Future of Geotechnical Engineering. As we move into the future, the demands of population growth, the increasing shortage of suitable land, and environmental concerns will mean that civil engineering structures will need to be located at sites previously considered unsuitable due low geotechnical integrity. The increased boldness of structural designs in terms of the heights and sizes of buildings and other structural systems also will pose challenges for engineers involved in designing their foundations. Geotechnical engineers of the future must develop new skills and technologies that would enable such projects to be possible. A case in point is the Chubu Centrair International Airport, which was constructed on a man-made island in Japan's Ise Bay (Figure 1.13). Future enhanced technologies will be required for future civil engineering systems that are slated to be built on artificial islands to prevent excessive settlement and damage during earthquakes. Furthermore, future geotechnical engineers will increasingly include in their analysis, elements of



(*a*)

(*b*)

Figure 1.13 The Chubu Centrair International Airport, entirely built on an artificial island, posed a variety of complex challenges in geotechnical engineering [*Source:* (*a*) BehBeh/Wikimedia Commons and (*b*) Gryffindor/Wikimedia Commons].

uncertainty and reliability and will give greater prominence to earthquake science, geosynthetics, the geo-environment, and new, promising techniques for efficient and quick in situ characterization of subsoils (CETS, 1995). Geotechnical engineers will increasingly be called upon to consider resilience in their designs, for example, by developing and adopting cost-effective designs that reduce the vulnerability of civil systems to natural or man-made disasters. Finally, as the Earth seemingly enters a phase of global warming, polar ice caps will melt, leading to increases in sea and land groundwater levels. The resulting change in subsoil pore water pressures is expected to lead to drastic changes in geotechnical conditions, possibly threatening the stability of existing structures. As such, future geotechnical engineers may need to revise their design processes for future geotechnical structures, carry out continual performance reviews of existing geotechnical structures to assess their vulnerability to this threat, and to prescribe and implement remedial actions that may be needed. Future geotechnical engineers will be increasingly called upon to tackle nontraditional problem types as well, such as geo-environmental engineering, geosynthetics design and evaluation, and design of foundations for deep-water offshore structures for which there is relatively little available experience to provide guidance. In such situations, the geotechnical engineer's judgment and experience will be stretched to the limit (ASCE, 2005).

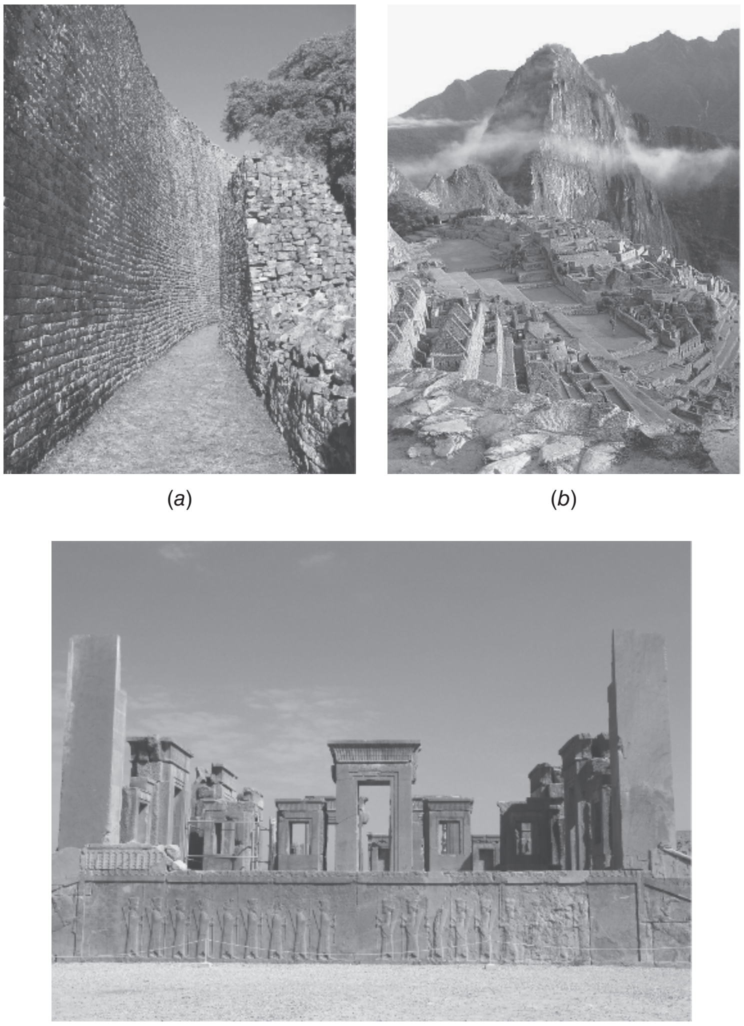
1.2.6 Construction Engineering

Construction engineers plan and manage the construction of architectural or civil engineering structures and systems. They are typically skilled in engineering, management, finance and economics, legal procedure, and human behavior. The tasks undertaken by construction engineers, either directly or through their site representatives, include planning and scheduling, cost monitoring and control, material and equipment procurement, design of mixes (e.g., concrete, asphalt, etc.), quality assurance and quality control of workmanship and materials, site geodetic surveys, and worker safety. In some cases, depending on the type of contract, construction engineers also supervise the design of structures on the site. Experienced construction engineers often assume the role of project manager.

History of Construction Engineering. Construction engineering may be considered the oldest of the civil engineering disciplines. As we learned in Section 1.1.2, the abandonment of nomadic lifestyles generated the need for permanent structures, which required that inhabitants acquire construction skills. For many centuries, the construction engineer was also the architect and the structural engineer and was called the master builder in many early civilizations.

Some of the earliest human feats in construction engineering are evidenced in archeological remains of the city of Babylon, located 50 miles south of Baghdad in modern day Iraq between the Tigris and Euphrates Rivers in 6000–3000 BC. This city is known for its canal networks, organized layouts, and building structures. Many of the houses were two and three stories high, and the city's streets were constructed in a grid fashion relative to the river (at right angles or parallel). Also, there is archaeological evidence that the city had an elaborate sewerage system that consisted of feeder pipes from residences to main sewer pipes located beneath the streets (PMB, 2008). In present-day Malta, there is evidence of the construction engineering feats of the ancient people of the Ghar Dalam phase of the country's history, including the megalithic temples of Malta, circa 5000 BC.

Of the ancient Near East, the ziggurat is the most distinctive infrastructure. Similar to ancient Egyptian pyramids, most of these structures were four-sided, and built to great heights to reach the "realms of the gods." However, unlike the smooth-surfaced pyramids of Egypt, ziggurat exteriors were tiered to facilitate the construction work and supervision and also to accommodate religious rituals essential to the societies at the time. The lower parts of surviving ziggurat remains are indicative of remarkable design and construction engineering techniques. For example, the temple's core (comprising unbaked mud brick) becomes alternatively more or less damp depending on the season, and the constructors provided holes through the temple's baked exterior layer to allow the evaporation of moisture from the core. Also, drains were engineered along the ziggurat's terraces to drain storm water (German, 2012). During the ancient Egyptian civilization circa 3000 BC, several structures to serve various functions were constructed under a succession of kings, notably Menes and Scorpion. These structures included temples, tombs (pyramids), and hydraulic structures (dams, retention basins, canals, irrigation ditches, and dikes). Demonstrating great skill in engineering, the constructors of facilities in that civilization used relatively sophisticated machines, such as the lever, inclined plane, and roller, to transport bulky building materials and ultimately to erect large structures such as the Great Pyramids of Giza and Cheops. Circa 2550 BC, Imhotep, considered by many as the first engineer, used shaped stones, simple construction tools, and mathematics to build the famous stepped pyramid of King Zoser located at Saqqarah in ancient Egypt (Saouma, 2007). Other notable products of ancient construction engineers included the Persepolis in Iran in 500 BC (Figure 1.14*c*), Parthenon by Iktinos in ancient Greece (circa 440 BC), the Great Wall of China (circa 200 BC), and the Coliseum in Rome in AD 72. Also, ancient civilizations such as those of Crete, Greece, and Rome, constructed significant civil engineering structures. In the 7th century



(*a*) (*b*)

(*c*)

Figure 1.14 A few instances of remaining evidence of the skills of ancient constructors: (*a*) conical tower of Great Zimbabwe, circa AD 11 (*Source:* Vinz at fr.wikipedia), (*b*) ruins of civil structures in Machu Picchu, a pre-Columbian Inca city located in present day Peru (*Source:* Charlesjsharp/WikipediaCommons), (*c*) structures constructed by Darius I in 500 BC, in Persepolis, ceremonial capital of the Achaemenid Empire, present-day Iran (*Source:* Wikimedia Commons).

AD in India, Brahmagupta, an Indian mathematician and astronomer, used arithmetic based on Hindu–Arabic numerals to determine the volume of material associated with excavation projects (Plofker, 2007).

In AD 11, the Kingdom of Great Zimbabwe constructed an impressive huge complex of stone walls that undulated over 1800 acres of terrain in present-day Zimbabwe (Figure 1.14*a*). Constructed from closely fitted granite blocks taken from exposed rocks in the surrounding hills, the walls were given nicely finished surfaces. The rocks were broken into portable sizes and fitted without using mortar by laying them on top of each other. Each rock layer was recessed slightly more than the previous layer to yield a self-stabilizing inward slope (MetArt, 2009).

In the ancient Roman Empire, circa 20 BC to several centuries AD, construction was often guided by the documented manuals written by master builders, the most famous of which was Vitruvius. These manuals included descriptions of the knowledge required of an architect and builder, building materials and their use, rules of building design, design of columns, water collection and supply, and contemporary building equipment such as hoisting gear. The manuals also contained theoretical information such as the basic principles of mechanics. The Pont du Gard Aqueduct, located near Remoulins in southern France, was constructed by engineers from the ancient Roman Empire circa 19 BC to AD 70. The aqueduct was constructed in three years using a workforce of about a thousand people using large stones without any binding mortar. The stones were cut to fit together, thus eliminating the need for cementitious material, and the stones were raised to fit their designed positions using a block-and-tackle technique, the winch for which was powered by a massive human treadmill. The constructors erected a complex protruding scaffolding system comprised of ridges and supports (Straub, 1964).

Yet another example of the remarkable construction skills of past civilizations is Machu Picchu, a pre-Columbian Inca city constructed at the height of the Inca Empire circa 1450. Considered a civil engineering marvel of the ancient world, Machu Picchu is located 2400 m (7880 ft) above sea level in the Urubamba Valley on Peru's side of the Andes Mountains (Figure 1.14*b*). Machu Picchu was constructed by ingenious people who demonstrated their skills in constructing resilient structures for running water supply and distribution, drainage, and food production.

The Future of Construction Engineering Systems. The future landscape of construction engineering is likely to be characterized by applications of advancements in materials science, computer and information technology, automation, project delivery, and supply of materials. Engineers will utilize information technology tools such as computer simulation to enhance the construction process. These tools include computer-aided design (CAD) and computer-aided installation/construction. Emerging technologies in this area include life-sized three-dimensional visualizations that enable the construction engineer to "walk" through the project at any stage of the construction process.

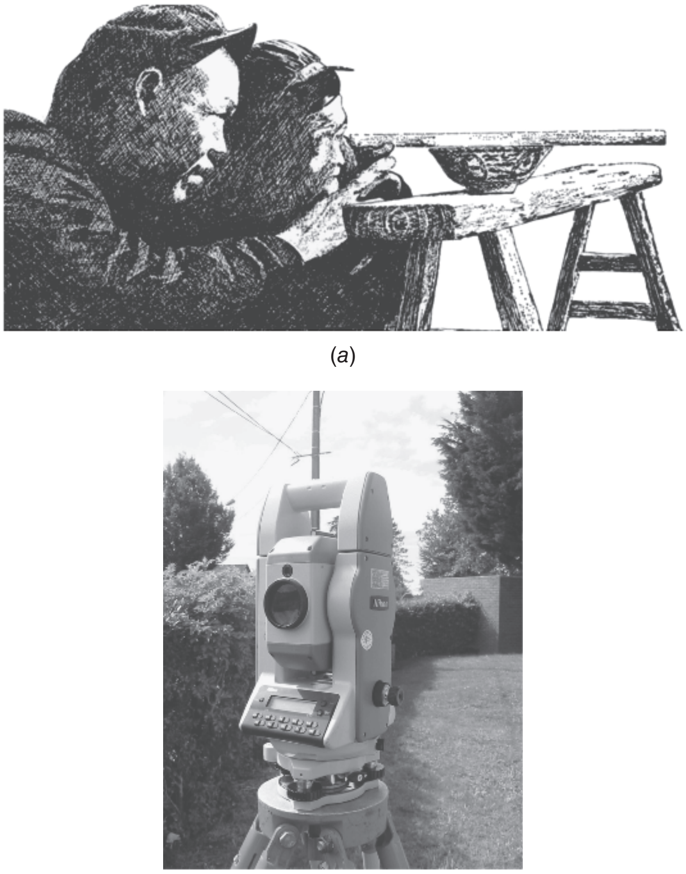
Also, production management principles will be increasingly applied to architectural, engineering, and construction (AEC) systems. These will include new techniques in project management and delivery, including Scalable Enterprise Systems, and new directions in management that are expected to help create and maintain effective teams and auspicious environments. Virtual reality will be used as a tool for seamless integration of processes in the AEC industry. The behavior of construction products and processes will be monitored or optimized using simulation and analytical modeling techniques. Engineers will strive toward adopting concurrency in construction systems. Also, construction engineering systems will be stretched to higher limits due to increasingly bold civil and architectural material processing and designs. For example, three-dimensional "printing" using concrete or other materials is expected to enhance construction efficiency and overall sustainability of civil engineering systems. Construction engineers and managers also will seek to carry out evaluations of alternative contracting approaches or project delivery mechanisms on the basis of a wider range of criteria, such as the impacts on owners, users, and the community, in terms of initial cost, life-cycle cost, environmental sustainability, and economic development. Furthermore, innovations in spatial monitoring, such as global positioning systems and remote sensing, will be increasingly applied in construction supply chain management and project monitoring.

1.2.7 Geomatic Engineering

One of the oldest activities of civil engineering and to this day an indispensable aspect of civil engineering work (Mikhail, 2003), geomatic engineering is the science of accurate establishment of the position of points on the Earth's surface for purposes of establishing reference points and boundaries for natural or man-made objects. Thus, the field includes the design and layout of public infrastructure systems and mapping and control surveys for civil construction projects. The term "geomatics" incorporates the older discipline of surveying with newer spatial data collection and management sciences such as Geographic Information Systems (GIS), GPS, and related forms of Earth mapping. A formal definition of geomatic engineering is "a modern discipline which integrates acquisition, modeling, analysis, and management of spatially referenced data that uses the framework of geodesy to transform spatially-referenced data from different sources into common information systems with well-defined accuracy characteristics." The evolution of surveying to geomatics was spawned by the advancements in digital data processing, and thus the work scope of professional surveyors has transcended beyond those associated with surveying only. Other related and relatively new fields include hydrogeomatics, which evolved from hydrographics and represents the study of surveys of areas on, above, or below the surface of water bodies. Geodetics is the measurement and representation of the Earth in a three-dimensional time-variant space. Geodetic engineers also measure global geodynamical phenomena including the motion of the Earth's crust and movement of the poles.

Geomatic engineers integrate science and technology from both new and traditional disciplines, such as geodesy (or geodetic engineering), photogrammetry, cartography, remote sensing, GPS or Global Navigation Satellite Systems (GNSS), and GIS or geoinformatics, and computer-aided visualization. Geomatic engineers play a critical and continuing role in civil engineering systems development by collecting, archiving, and maintaining diverse spatial data on such systems. Over the past decade, advances in computer science and information technology, remote sensing technologies, and other disciplines have spawned significant advancements in geomatics. In response, a number of university departments and agency divisions that once had names containing the words "surveying," "survey engineering," or "topographic science" now have been renamed to include words such as "geomatics," "geomatic science," or "geomatic engineering." The equipment used for geomatic work has evolved from basic tools such as meniscus straws to compasses and calibrated chains, and then to robotic total stations that are fully computerized, equipped with multiple digital cameras, and capable of long-range laser scanning and intelligent recognition of scanned features (Figure 1.15). Other equipment in current use include LIDAR (light detection and ranging), an optical remote sensor that measures geomatic attributes of targets by illuminating the target with laser beams and interpreting the response.

The History of Geomatic Engineering. Ancient records show that surveying has always been an integral part of civil engineering systems development. In ancient Egypt, a land register existed circa 3000 BC, and the use of that document and simple geometry was critical in reestablishing property boundaries after each seasonal overflow of the Nile River, which washed out the physical markings of these boundaries. Devices used for these surveys included a right-angled triangle with a 3:4:5 side ratio. The skill of the ancient Egyptians in surveying is evidenced in the almost perfect dimensions, shapes, and north–south orientations of their pyramids, such as the Great Pyramid of Giza built circa 2700 BC. Other evidence of human long-standing dependence on surveying skills include Stonehenge (circa 2500 BC) where monuments were "set out" by that era's surveyors using rudimentary tools and techniques. In the BC–AD transition era in ancient Rome, the construction of aqueducts and other large structures was facilitated by the use of three kinds of



(*a*)

(*b*)

Figure 1.15 Basic survey instruments—the ancient and the new. (*a*) Floating sights water-level proto-theodolite, in ancient China. The bamboo tube floats on the convex meniscus of water in a rice bowl (*Source:* Needham et al., 2001). (*b*) Robotic Total Station (PhY/Wikimedia Commons).

surveying instruments (Figure 1.16): *dioptra*, a sighting tube with a sight at both ends and attached to a stand (when fitted with protractors, a dioptra could be used for angular measurements); the *groma*, which consists of "a vertical staff with horizontal cross-pieces mounted at right-angles on a bracket (each cross-piece had a plumb line hanging vertically at each end) and was used to survey straight lines and right-angles"; and the *chorobates*, a leveling tool that comprised a wooden beam fitted with a water level with supports at both ends (Lewis, 2001a).

Ancient Persian scholar Abu Rayhan al-Biruni of Kath (in present-day Uzbekistan) is regarded as the father of geodesy for his important theoretical contributions to the field in that era. In ancient Rome in AD 300, land surveyors, who enjoyed privileged professional status, established the basic dimensional measurements for purposes of administrative division of the empire. In 1086 in England, a surveying document was established by William the Conqueror to contain spatial as well as socioeconomic and physical features data about each land parcel. In continental Europe, the Cadastre, founded by Napoleon Bonaparte in 1808 and considered by that

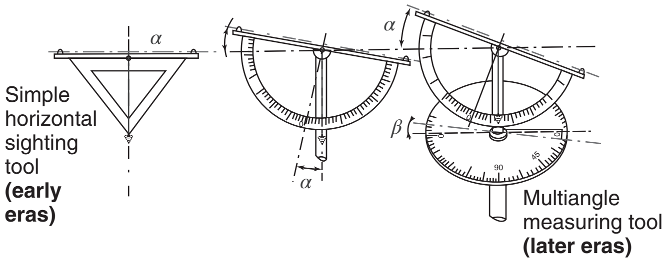


Figure 1.16 Form evolution of the dioptra, an ancient survey instrument (Nerijp/Wikimedia Commons).

ruler to be one of his greatest achievements in civil law, contained the land location, dimensions, value, ownership, and the like and used scales of 1:2500 and 1:1250.

Historically, equipment to measure distances included chains with links of a known length, and a compass was used to measure horizontal angles. Subsequent improvements included the use of carefully scribed disks for enhanced angular resolution, mounting telescopes with reticules precise sighting (such as theodolites), and the use of calibrated circles that allowed surveyors to measure vertical angles. For measuring height, surveyors have traditionally used the altimeter, a barometer that uses changes in air pressure as an indication of changes in vertical distance. Over the years, the need for greater accuracy led to the development of instruments that utilize a calibrated vertical measuring rod to provide a plane for measuring height differences between the instrument and the point in question. Modern instruments include the total station, essentially a theodolite fitted with an electronic device to measure distance. Total stations have evolved from optical-mechanical instruments to computerized and robotic equipment that are linked wirelessly to other offsite systems such as GPS, computers, and printers.

The Future of Geomatic Engineering. In the foreseeable future, the field of geomatic engineering will continue to undergo rapid changes due to technological developments in digital imaging, artificial intelligence, laser sensing, and global positioning systems and other technologies. These ongoing and other emerging technologies are expected not only to revolutionize regular surveying engineering tasks but also to impact a myriad of applications in several other fields of engineering, science, and the humanities where it is valuable to acquire information on near-real-time positioning of systems and phenomena (Mikhail, 2003). Also, the future is expected to see increased use of geomatic techniques for monitoring the stability of large civil structures in terms of their shape deformation arising from internal and external stressors.

1.2.8 Civil Materials Engineering

The choice of material for civil engineering systems construction is influenced by a variety of factors, including the initial and life-cycle maintenance cost, mechanical properties, durability, ease of construction, and aesthetics (Ho, 2003). To make informed decisions on material choices, the materials engineer typically solicits mechanistic or empirical data on the performance of the material in response to environmental factors that include usage and climate/weather. Thus, civil materials engineering involves the investigation of the properties of construction materials such as the raw ingredients for construction (e.g., cement, water, steel, aggregates, subgrade, subbase/base courses, etc.) and mixed products (e.g., asphaltic and Portland cement concrete, etc.) to ascertain their suitability or to recommend ways to enhance their properties for that purpose. The field of civil materials engineering is an interdisciplinary one that investigates the relationships between the composition and structure of materials and their properties. With the current explosion in nanoscience and nanotechnology, materials engineering is playing a more visible role in many institutions. Materials engineering also includes forensic engineering and thus covers the study of the failure of civil engineering systems.

The nature and behavior of any material are governed by its constituent elements and the manner in which it was synthesized. Materials engineers seek to understand the fundamental structure and behavior of existing materials with a view to expanding their uses and the development of new or enhanced materials with specific desired properties. They relate the atomic structure of that material to the properties and performance of the material when it is used in a given application.

Subfields of civil materials science or engineering include nanotechnology, which studies and develops materials at an atomic level; microtechnology, which includes the microfabrication of materials at micrometric level; crystallography, which studies the solid space filling behavior of atoms, the nature of crystal forms or structures, and the characterization of crystal forms as related to their performance and physical properties; materials characterization, which studies the properties of materials using equipment for spectroscopy, thermal analysis, chromatography, and electron microscope analysis. Other subfields include tribology, which is the study of material wear due to external agents such as friction, and surface science, which studies structures and interactions between material phase interface (solid–gas, solid–liquid, or solid–solid).

With regard to material types, subfields in materials engineering include metallurgy (the study of the extraction, processing, and modification of metals and their alloys), biomaterials (materials that are used in or derived from biological systems), and ceramography (which involves ceramic microstructures including transformation-toughened ceramics and polycrystalline silicon carbide).

Recent emerging applications of materials science, particularly of materials characterization, can be found in the area of civil engineering systems monitoring; namely, the deterioration of physical systems (e.g., corrosion of a steel bridge element, age-induced cracking of a pavement, rusting of sewer pipes, etc.) can be quickly detected by available techniques (because they involve a change in the material and hence the material's properties) before these structures suddenly fail and cause possible loss of life or property, or injury.

History of Civil Materials Engineering. Over the ages, the dominance of a new material used in a given era has often defined the progress of that era. For example, we have had the Stone Age, the Bronze Age, and the Steel Age. In ancient Greece and Rome, dry rocky soil yielded building materials that were durable. Harbors were built using large stones that were sunk under their own weight, and quay walls and smaller jetties were constructed of concrete comprised of broken stone, lime, and pozzuolana–a material that has survived the punishing marine environment for over 2000 years and can still be seen along the coasts of Campania, Latium, Pozzuoli, Fornia, and Anzio in Italy. In the Mesopotamia region, where there was little natural stone, engineers in the cities of Assyria and Babylonia depended on brick as the main building material. The ruins of the Tower of Babel, excavated in the early 20th century, revealed a core of unburned bricks surrounded by a shell of burnt brick. As a binding agent, bitumen was sometimes used instead of mortar (Straub, 1964).

Materials science, particularly the engineering of materials to yield new materials of desired physical properties, is one of the oldest forms of engineering and applied science and takes its roots from the manufacture of ceramics and in the last millennium, metallurgy. Indeed, the timeline of materials development include (TMS, 2012) the firing of ceramics (circa 28,000 BC) found at sites in the Pavlov Hills of Moravia; copper metallurgy (by hammering) for decoration by the Old World Neolithic peoples circa 8000 BC; extraction of copper from azurite and malachite and reshaping molten metal in Turkey circa 5000 BC; iron smelting in Egypt in 3500 BC; metal mixing in 3000 BC to produce bronze in Syria and Turkey; invention of glass in northwestern Iran in 2200 BC; production of porcelain in 1500 BC in China; and crucible steel making in India in 300 BC. In AD 400, iron smiths in Delhi, India, forged and erected a 20-ft-high iron pillar that has defied environmental degradation up to today. Other significant watermarks include the publication in the 1540–1600 period of *De La Pirotechnia* by Vannoccio Biringuccio, the first written account of proper foundry practices, *De Re Metallica* by Georgius Agricola, a description of mining and metallurgy practices in the 16th century, and *Della Scienza Mechanica* by Galileo, which scientifically analyzes the strength of materials. In 1755, John Smeaton invented hydraulic cement, thus introducing modern concrete, the dominant construction material of the modern age, and in 1805 Luigi Brugnatelli invented electroplating. In 1827, Wilhelm Albert developed iron wire rope, paving the way for large-scale construction involving steel cables. In 1864 Dmitri Mendeleev developed the Periodic Table of Elements which, to this day, serves as a reference tool for characterizing and identifying basic materials in engineering. This was followed by the invention of dynamite by Alfred Nobel in 1867, which facilitated large-scale civil engineering construction in rock terrain (TMS, 2012).

The field of materials science experienced a major breakthrough in the late 19th century when Willard Gibbs, an American theoretical physicist and chemist, established a relationship between the physical properties of a material and its thermodynamic properties in relation to its atomic structure in various phases. This finding laid the critical basis for understanding material behavior. In the last millennium, advancements in the field were spawned by the need to develop new materials for purposes of space exploration, which included metallic alloys, silica, and carbon materials that are typically used in constructing space vehicles. In the mid-20th century, many materials science departments and divisions in industry and academia were renamed metallurgy departments due to emphasis on metals. However, in recent years, many are reverting to the original name (materials science) because the field has broadened to include a broad array of material classes and types, such as ceramics, polymers, semiconductors, magnetic materials, and other innovative materials that are useful in civil engineering systems design and operations.

The Future of Materials Science and Engineering (MSE). In the near future, the study and application of materials in civil engineering is expected to include geosynthetics (geotextiles, geomembranes, and geogrids). Enhanced versions of these products will be used in embankments on soft foundations or to protect erosion-prone slopes (Holtz, 1991). Due to the adoption of intelligent materials and intelligent designs, there is expected to be an increasing number of energy-efficient buildings and other civil structures (Apelian, 2007). As case in point, Germany's Institute of Solar Energy Systems has developed a technique that uses a thin layer of material containing microencapsulated paraffin to carry out temperature equalization; when temperature inside the building rises above 24°C, the enclosed paraffin in the wall melts, leading to heat reduction in the room. Then at times of low temperature, the paraffin solidifies, releasing the stored heat, leading to energy savings and pollutant reduction. The future seems to be promising for discoveries in intelligent, green, and energy-efficient materials. Another example of future trends in this area is exemplified by roofing system applications such as the Teflon-coated fiberglass membrane roof that was used for the Riyadh International Stadium in Saudi Arabia and self-healing bioconcrete. Future world needs are projected to include recyclable or biodegradable materials. Environmental quality will be enhanced by the use of new biodegradable natural plastics for packaging of goods. Other similar materials including fiber-reinforced polymers (Figure 1.17) will see increased use due to their desirable engineering properties, low life-cycle cost, and contribution to sustainable development. As designers of structural systems demand less weight with greater strength, the focus will be on lightweight structural materials, specifically in the areas of alloys that can be stiffened to the extent needed). The properties of strength, ductility, weight,

Figure 1.17 Use of fiber-reinforced polymers can enhance sustainable design (Courtesy of EVOLO, LLC).

and recyclability, therefore, will continue to guide the development of new materials for future civil engineering systems.

1.2.9 Architectural Engineering Systems

This branch of civil engineering deals with the technological aspects of architectural structures and, therefore, includes study of the behavior and properties of building components and materials, environmental system design and analysis, and building operation. Architectural engineers strive to develop optimal design of buildings and building components and facilities within constraints that include physical space, material strengths, and cost; to achieve this objective, they use domain knowledge in civil and mechanical engineering including structural mechanics, materials science, geomatics, energy science and technology, acoustic science and systems-based tools including economic efficiency, multiple criteria optimization, and computer modeling, simulation, and visualization. Architectural engineers also pay close attention to issues of building resilience to external and internal threats and the sustainability of the buildings physical structure and operations.

The environmental aspect of building systems typically accounts for a dominant fraction of overall building operating cost and includes a wide range of areas, such as heating and air conditioning, lighting and acoustics, building power and energy systems, plumbing and piping, vertical and horizontal transportation, occupant safety, and fire protection. As such, architectural engineers are familiar with a great number of building codes covering these and other related areas. Architectural engineers deal with all phases of building systems development: planning, design, construction, operation, monitoring and inspection, maintenance, and renovation or decommissioning. At each of these phases, the architectural engineer engages in a variety of tasks, including selecting the best option on the basis of cost, occupant safety, environmental impacts, and other considerations.

In countries such as the United Kingdom, Canada, Australia, and some African and Asian countries, architectural engineering is more commonly known as building engineering, building services engineering, or building systems engineering. Architectural engineers work closely with architects and are conversant with architectural features that influence the building performance in terms of cost, energy efficiency, ventilation, and the like.

Many structures in civil engineering are being designed to minimize the use of resources by incorporating features that reduce the needs for energy, water, and lighting. This has been the case for buildings mostly but is also being gradually adopted in other civil structures. The Bahrain World Trade Center towers in Manama, Bahrain, is designed as the world's first skyscraper to incorporate wind turbines in its design; the sail-shaped buildings on either side are designed to funnel wind through the gap to guide wind to three wind turbines installed at three different levels of the building (Figure 1.18). Other notable examples of green buildings are the Centers for Disease Control and Prevention Laboratory Sciences Building in Atlanta, Georgia; Santa Monica's Z6 House (the 6 represents the goal of attaining zero levels of six factors: water, carbon, emissions, waste, energy, and ignorance); Colorado Court Affordable Housing Project, Chicago's Factor-10 House (which is said to consume only a tenth of the environmental resources consumed by an average home); the Lewis Center for Environmental Studies in Oberlin College, Ohio; the Solar Umbrella House in Venice, California; the Resource Center for the Homeless in Austin, Texas; the Wayne L. Morse U.S. Courthouse in Eugene, Oregon; Genzyme's headquarters in Cambridge, Massachusetts; and Toyota's headquarters in Torrance, California (Apelian, 2007; McGrath, 2012). We will acquire a

Figure 1.18 An example of future building systems concepts.

greater appreciation of sustainability in Chapter 28 where we will discuss the principles and benefits of sustainable development.

1.3 FINAL COMMENTS ON THE HISTORICAL EVOLUTION AND FUTURE OF CIVIL ENGINEERING SYSTEMS

A useful conclusion to this chapter would be to discuss the overall context of the evolution of civil engineering systems in terms of their relationships with socioeconomic systems, the different philosophies of design, the cumulative nature of knowledge in civil engineering systems development over the centuries, and future directions in general.

Civil engineering systems that were developed in early civilizations included public buildings, temples, fortifications, roads, irrigation canals, and water supply structures. Over the ages, these systems evolved in their design and construction features to enhance the quality of life of the people through the provision of shelter, water, sanitation, protection, and transportation of goods and services. In the current era, the situation is no different as society continues to depend on good physical infrastructure to enhance the quality of life. In fact, even with the advent of nonphysical infrastructure such as the Internet, there still exists a need, greater than ever before, for physical infrastructure to provide buildings, transportation, clean water, waste disposal and treatment, among others (Dandy et al., 2008).

For the design and construction of civil engineering systems across the civilizations and over the millennia, there existed two philosophies: those that were utilitarian in nature and those that were devotional (Straub, 1964). The lessons from these philosophies are important as civil engineers strive to incorporate sustainability considerations in their system designs. The Romans and Persians developed systems that were consistent with the utilitarian philosophy as they were mainly built for purposes of military strategy and commerce. On the other hand, the civil systems built by the Greeks were primarily of devotional value first and other values second. The Greek animistic conception of nature, which ascribed a living soul to mountains, rivers, and valleys, caused them to shy away from violent interference with natural land forms and obstacles. A parallel to this dichotomy can be found in the two rival moralities that guided the design and construction of hydraulic and other civil engineering systems in ancient China (Needham et al., 2001). The first morality was the Confucius philosophy (confining and repressing nature and thus advocating masculine activities such as dike construction), which was similar to the Roman and Persian approaches. The second was the Taoist philosophy (greater freedom for natural courses and thus advocating the use of feminine activities such as dredged concavities), which was similar to the Greek approach.

Also, the current state of civil engineering systems is the culmination of the collective efforts of several different civilizations at different locations all over the globe and over time. These civilizations, some to a greater extent than others, passed on their knowledge to successive ones through scholarly exchanges, trade, migration, documentation, or oral traditions. The development of civil infrastructure over the centuries began to be characterized by specialization, not only with respect to the type of civil system in question (e.g., transportation engineering, environmental engineering, structural engineering, etc.), but also with respect to the phase of facility development (e.g., construction engineering for the construction phase and traffic engineering for the operations phase).

As we move into the new millennium, the basic needs of society will remain largely unchanged, but the means by which engineers satisfy those needs will change enormously (Dandy et al., 2008). The advancement of civil engineering systems will continue to guide (and be guided by) changes in the socioeconomic and natural environments and will be catalyzed by rapidly expanding frontiers in science and information technology. Social and economic changes constantly create new demands on both engineers and the educational systems that produce them (Labi, 1997; ASCE, 2001). It is therefore important that engineers cultivate the ability to make informed choices, basing their judgments and decisions not only on the analysis of present situations but also on the vision of a preferred future (Berkovski and Gottschalk (1996). Along similar lines of thinking, the National Academy of Engineering, in its 2004 *Vision for the* ***E****ngineer of 2020* (NAE, 2008), and the American Society of Civil Engineers, in its 2007 ***Vision for Civil*** *Engineering in 2025* (ASCE, 2007) and 2008 *Book of Knowledge* (ASCE, 2008), presented their visions of the preferred skill sets of future civil engineers. Other organizations duly recognize that issues that will become critical in the development of future civil engineering systems include sustainable decision making, interoperability between different sectors, climate change impacts, and smart infrastructure.

SUMMARY

Since the dawn of human existence, the economic and cultural prosperity of nations have been very closely linked with the level of technological advancement. In presenting the historical evolution of civil engineering, we have shown that the development of engineering infrastructure has led to, or has been the result of, the socioeconomic advancements of extraordinary civilizations dating as far back as the Sumerian civilization in Mesopotamia in 7000 BC. We also have shown that civil engineers, or persons acting in that capacity, have always executed their work from a systems perspective at least implicitly, and that these subbranches could be enhanced if systems approaches were incorporated in an explicit manner. Many of the basic concepts of systems analysis in civil engineering were discussed in this chapter and were shown to be consistent over time. Civil engineers have applied their knowledge to plan, design, build, maintain, or/and operate complex civil infrastructure systems that have served humankind in a variety of ways, including buildings for residential, commercial, and industrial purposes; facilities for transporting passengers and freight; pipe networks for supplying water; and facilities for waste disposal. For each branch of civil engineering, a brief history, description of typical tasks, and future directions was provided in this chapter, thus setting the stage for Chapter 2 which discusses the general systems perspective, including the phases of and tools for developing systems in any branch of civil engineering.

EXERCISES

1. Discuss any two definitions of engineering and identify the systems engineering concepts that are found in these definitions.
2. Is civil engineering both an art and a science? Explain.
3. N. W. Dougherty stated: “The ideal engineer is a composite…. He is not a scientist, he is not a mathematician, he is not a sociologist or a writer; but he may use the knowledge and techniques of any or all of these disciplines in solving engineering problems.” Discuss.
4. According to R. E. Hellmund, engineering “brings about the utilization of the materials and laws of nature for the good of humanity.” However, it can be a two-edged sword. Discuss how poor engineering practice could be harmful to society.
5. Discuss the sociological changes in prehistoric times that ultimately led to the need for civil engineering structures.

6. It is desired to extend an existing rail transit line to serve outlying areas of a large city. Identify the various types of civil engineers who likely would be involved over the life of the system.
7. For any one branch of civil engineering, in your own words, discuss the evolution of that branch over the millennia and how developments in other fields fostered advancements in that branch.
8. Discuss the differences between any two rival philosophies of civil engineering systems design, citing examples from past civilizations. Include a discussion of your preferred philosophy in the context of civil engineering systems resilience and sustainability.

REFERENCES

Abbot, M. B., Babovic, V. M., and Cunge, L. A. (2001). Towards the Hydraulics of the Hydroinformatics Era. *J. Hydr. Res.* 39, 339–349.

ABET (1993). *Definition of Engineering*. Accreditation Board for Engineering and Technology, Inc., Baltimore, MD.

Apelian, D. (2007). Looking Beyond the Last 50 Years: The Future of Materials Science and Engineering, *J. Minerals, Metals & Materials Soc*. February 2007 Issue, 65–73.

ASCE (2000). *Judgment and Innovation: The Heritage and Future of the Geotechnical Engineering Profession*. Geotechnical Special Publication No. 111, S. Francisco, and E. Kavazanjian, Jr., Eds., ASCE/Geo Institute, Reston, VA, p. 133.

ASCE (2001). *Engineering the Future of Civil Engineering*. Am. Soc. Civil Eng., Reston, VA.

ASCE (2007). *Vision for Civil Engineering in 2025*. Am. Soc. Civil Eng., Reston, VA.

ASCE (2009). *Brochure on ASCE's History and Heritage Program*. Am. Soc. Civil Eng., Reston, VA.

ASCE (2008). *Civil Engineering Body of Knowledge for the 21st Century*, 2nd ed. Am. Soc. Civil Eng., Reston, VA.

Atalay, B., and Wamsley, K. (2009). *Leonordo's Universe*, National Geographic.

Baker, M. N., and Chow, V. T. (1964). *Handbook of Applied Hydrology*. V. T. Chow, Ed. McGraw-Hill, New York.

Baker, M. N., and Taras, M. J. (1981). *The Quest for Pure Water-The History of the 20th Century*, American Water Works Association, Deriver, CO.

Benton, J. R., and DiYanni, R. (1998). *Arts and Culture: An Introduction to the Humanities*. Prentice-Hall, Upper Saddle River, NJ.

Berkovski, B., and Gottschalk, C. M. (1996). Strengthening Human Resources for the 21st Century: UNESCO Engineering Education and Training Program, *European Journal of Engineering Education* (21)1, 3–11.

Biswas, A. (1970). *History of Hydrology*. North Holland, London.

Buescher, C. (2000). *Water Supply and Wastewater Engineering, Environmental Engineer*. AWWA.

Carr, T. J. (2011). The Harappan Civilization. http://www.archaeologyonline.net.

CETS (1995). *Probabilistic Methods in Geotechnical Engineering*. Commission on Engineering and Technical Systems, The National Academies, Washington, DC.

Chanson, H. (2007). Hydraulic Engineering in the 21st Century: Where to? *J. Hyd. Res.* 45(3), 291–301.

Chrimes, M., and Bhogal, A. (2001). *Civil Engineering – A Brief History of the Profession: The Perspective of the Institution of Civil Engineers*, in *International Engineering History and Heritage – Improving Bridges to ASCE's 150th Anniversary*. ASCE, Reston, VA.

Dandy, G., Walker, D., Daniell, T., and Warner, R. (2008). *Planning and Design of Engineering Systems*, 2nd ed. Taylor and Francis, London, UK.

Darling, D. J. (2003). *The Complete Book of Spaceflight: From Apollo 1 to Zero Gravity*. Wiley, Hoboken, NJ.

Delleur, J. (2003). *Hydraulic Engineering, Handbook of Civil Engineering*. CRC Press, Boca Raton, FL.

Dugas, R. (1988). *A History of Mechanics*. Courier Dover, Mineola, NY.

EB (2011). *Encyclopedia Britannica*. Encyclopedia Britannica Inc., Chicago, IL.

Ellis, H. (1968). *The Pictorial Encyclopedia of Railways*. Hamlyn Publishing, Feltham, UK.

FitzSimons, N. (1996). Benjamin Wright, The Father of American Civil Engineering, in *Civil Engineering History—Engineers Make History*, J. R. Rogers, D. Kennon, R. T. Jaske, F. E. Griggs, Eds. Procs., 1st National Symposium on Civil Engineering History, ASCE, Reston, VA.

Fricker, J. D., and Whitford, R. K. (2005). *Fundamentals of Transportation Engineering*. Prentice Hall, Upper Saddle River, NJ.

German, S. (2012). Ziggurat of Ur, Khanacedemy. smarthistory.khanacademy.org. Accessed Dec. 15, 2012.

GulfNews (GN) (2010). Burj Khalifa: Towering Challenge for Builders. GulfNews.com. 4 January 2010. Retrieved Feb. 10, 2010.

Harr, M. (2004). *Geotechnical Engineering, Civil Engineering Handbook*, 2nd Ed., CRC Press, Boca Raton, FL.

Heyman, J. (1998). *Structural Analysis: A Historical Approach*, Cambridge University Press, Cambridge, UK.

Hjorth, P., Kobus, H., Natchnebel, H. P., Nottage, A., Roberts, R. (1991). Relating hydraulics and ecological processes, in Hydraulics and the Environmental Partnership in Sustainable Development Issue, *J. Hydraulic Res.* 29, 8–19.

Ho, D. W. S. (2003). *Materials Engineering, Handbook of Civil Engineering*. CRC Press, Boca Raton, FL.

Holtz, R. (1991). Geosynthetics in Civil Engineering. In Use of Geosynthetics in Dams, 11th Annual USCOLD Lecture Series, US Commission in Large Dams, Plain Fields NY, pp. 1–19.

Holtz, R., and Kovacs, W. (1981). *An Introduction to Geotechnical Engineering*. Prentice-Hall, Englewood Cliffs, NJ.

ICE (2007). Institution of Civil Engineers' website. Accessed December 26, 2007.

Jacko, R. B. (2003). *Environmental Engineering, Civil Engineering Handbook*. CRC Press, Boca Raton, FL.

Khisty, J. C., and Mohammadi, J. (2001). *Fundamentals of Systems Engineering*. Prentice Hall, Upper Saddle River, NJ.

Kirby, R. S. (1990). *Engineering in History*. Dover, New York.

Kirby, R. S., Withington, S., Darling, A. B., and Kilgour, K. G. (1956). *Engineering in History*. McGraw-Hill, New York.

Kramer, S. N. (1963). *The Sumerians. Their History, Culture, and Character*. University of Chicago Press, Chicago.

Labi, S. (1997). *Vision of a Preferred Future*, in Imprints, College of Engineering Annual Report, Purdue University, West Lafayette, IN.

Lanciani, R., [1967 (first published in 1897)]. *The Ruins of Ancient Rome*. Benjamin Blom, New York.

Landels, J. G. (1978). *Engineering in the Ancient World*. UCLA Press, Los Angeles.

Leinhard, J. (2000). *The Engines of Our Ingenuity*. Oxford University Press, Oxford, U.K.

Lenkei, P. (2007). Climate Change and Structural Engineering. *Periodica Polytechnica, Civil Engineering* 51/2.

Leonard, K. M. (2001). Environmental Engineering, The World's Second Oldest Profession, in *International* Engineering History and Heritage—Improving Bridges to ASCE's 150th Anniversary, Procs., 3rd National Congress on Civil Engineering History and Heritage, Oct. 10–13, Houston, TX.

Lewis, M. J. T. (2001a). *Surveying Instruments of Greece and Rome*. Cambridge University Press, Cambridge, UK.

Lewis, M. J. T. (2001b). *Railways in the Greek and Roman World, Early Railways*. A Selection of Papers from the 1st International Early Railways Conference, A. Guy, J. and Rees , Eds., pp. 8–19.

Long, M., and Labi, S. (2011). Assessing the Vulnerability of Civil Engineering Structures to Long-term Climate Change, Conference on Vulnerability and Risk Analysis, University of Maryland, College Park, MD.

Liew, J. Y. R., and Shanmugan, N. E. (2004). *Theory and Analysis of Structures, Civil Engineering Handbook*, 2nd Ed.CRC Press, Boca Raton, FL.

Lyn, D. A. (2004). Fundamentals of Hydraulics, Civil Engineering Handbook, CRC Press, Boca Raton, FL.

Marhaba, T. (2000). *Crystal Clear: History and Issues in Drinking Water Disinfection, Environmental Protection*, Dallas, TX.

Magnusson, J. (2007). A Beautiful Tomorrow for Structural Engineering? *The Compass* 42(2), Oct. Issue.

McGrath, J. (2012). Sustainable Buildings. http://dsc.discovery.com/tv-shows/curiosity/topics/10-sustainable-buildings.htm. Accessed Dec. 15.

MetArt (2009). *Great Zimbabwe (11th–15th Century), Heilbrunn Timeline of Art History*. Metropolitan, Museum of Art, New York.

Moncur, M. (2012). The Quotations Page. www.quotationspage.com. Accessed Dec. 15.

Mikhail, E. W. (2003). *Surveying Engineering, Handbook of Civil Engineering*. CRC Press, Boca Raton, FL.

Museum of Art (2009). http://www.metmuseum.org. Accessed Nov. 10, 2009.

NAE (2008). *The Engineer of 2020: Visions of Engineering in the New Century*. National Academies Press, Washington, DC.

NASA (2002). *Celebrating a Century of Flight*. NASA Publication SP-2002-09-511-HQ, Washington, DC.

Nedwell, P. J., Swamy, R. N., and Nedwell, P. (1994). Ferrocement: Proceedings of the Fifth International Symposium on Ferrocement UMIST, Manchester, UK, Sept. 6–9.

Needham, J. (1986). *Science and Civilization in China*, Vol. 4, Part 3 Cambridge University Press, Cambridge, UK.

Needham, J., Gwei-Djen, L., and Wang, L. (2001). *Science and Civilization in China*, Vol. 4, *Physics and Physical Technology*, Part 3: *Civil Engineering and Nautics*, Cambridge University Press, Cambridge, UK.

Ochsendorf, J. A. (2005). Sustainable Engineering: The Future of Structural Design, Procs., 2005 Structures Congress & Forensic Engineering Symp.: Metropolis and Beyond, April 20–24, New York.

Osorio, N. L., and Osorio, M. A. (2006). History of Engineering, in *Using the Engineering Literature*, B. A. Osif, Ed. CRC Press, Boca Raton, FL.

Pannell, J. P. M. (1964). *Man the Builder—An Illustrated History of Engineering*. Jarrold and Sons, Norwich, UK.

Parkhill, S. T. (1998). 150 Years of Underground Design and Construction, in Engineering History and Heritage: Procs., 2nd National Congress on Civil Engineering History and Heritage, J. R. Rogers, Ed. Oct. 17–21, Boston, MA.

Petroski, H. (2001). *The Importance of Engineering History*. International Engineering History and Heritage, 1–7.

Plofker, K. (2007). *Mathematics in India. The Mathematics of Egypt, Mesopotamia, China, India, and Islam*: *A Sourcebook*. Princeton University Press, Princeton, NJ.

PMB (2008). The History of Plumbing. *Plumbing and Mechanical Magazine*, www.theplumber.com/history.html.

Prentice, J. E. (1990). *Geology of Construction Materials (Topics in the Earth Sciences)*. Chapman & Hall, 171, London, UK.

Prince, J. D. (1904). Review: The Code of Hammurabi. *Am. J. Theol.* 8(3), 3601–609.

Raju, V. R. (2010). *Ground Improvement Technologies and Case Histories*. Research Publishing Services, Singapore. Procs., 2005 Structures Congress and Forensic Engineering Symposium, Cambridge, MA.

Rao, A. R. (2002). *Surface Water Hydrology, New Directions in Civil Engineering, The Civil Engineering-Handbook*, 2nd ed., W. F. Chen and J. Y. Richard Liew, Eds. CRC Press, Boca Raton, FL.

Rayburn, W. (1989). *Flushed with Pride*. Pavilion, London.

Saouma, V. E. (2007). Lecture Notes in Structural Engineering, University of Colorado. Retrieved Nov. 2.

Shuter, J. (2008). *The Sumerians*, 2nd ed. Heinemann-Raintree, Chicago, IL.

Sinha, K. C. (2003). *Transportation Engineering, Handbook of Civil Engineering*. CRC Press, Boca Raton, FL.

Smoothwhirl. (2009). History of Civil Engineering. http://www.brighthub.com/engineering/civil/articles.

Straub, H. (1964). *A History of Civil Engineering—An Outline from Ancient to Modern Times*. MIT Press, Cambridge, MA.

Taras, M. J. and Baker, M. N. (1981). *The Quest for Pure Water: The History of the Twentieth Century*, Vol. 1. American Water Works Association, Denver, CO.

Terzaghi, K., Peck, R. B., and Mesri, G. (1996). *Soil Mechanics in Engineering Practice*, 3rd ed. Wiley, New York.

TMS (2012). The Minerals, Metals & Materials Society. www.materialmoments.org. Accessed Dec 15.

Voland, G. (1999). *Engineering by Design*. Prentice Hall, Upper Saddle River, NJ.

White, B. (2008). *Gaither's Dictionary of Scientific Quotations*. Springer, New York, NY.

USEFUL RESOURCES

Levy, M. (2000). *Engineering the City: How Infrastructure Works*, Chicago Review Press, Chicago, IL.

McCuen, R. H., Ezell, E. Z., and Wong, M. K. (2011). *Fundamentals of Civil Engineering*: An *Introduction to the ASCE Body of Knowledge*, CRC Press, Boca Raton, FL.

National Academy of Engineering (2004). *The Engineer of 2020: Visions of Engineering in the New Century*, National Academies Press, Washington, D.C.

Oakes, W. C., Leone, L. L., and Gunn, C. J. (2011). *Engineering Your Future: A Comprehensive Introduction to Engineering*, Oxford University Press, Oxford, UK.

Walesh, S. G. (2000). *Engineering Your Future*, ASCE Press, Reston, VA.

Wood, D. M. (2012). *Civil Engineering: A Very Short Introduction*, Oxford University Press, New York.