SOIL MECHANICS

Henry Petroski

Children play a hand game in which a closed fist represents a rock, two extended fingers, scissors, and an open palm, paper. At an agreed-upon signal, each of two players extends a hand in one of these configurations, and the winner is determined by the mnemonic, "rock breaks scissors, scissors cut paper, paper covers rock." The same game, modified slightly, could serve to introduce the engineering enterprise of building structures on the earth, with the fist again representing rock, an extended finger structure and an open palm soil, the relatively thin layer of "unconsolidated sediments and deposits of solid particles derived from the disintegration of rocks" otherwise known as earth or dirt. In this case rock supports structure, structure displaces soil and soil covers rock. This also suggests the sometimes surprising conditions that determine success or failure in a significant proportion of structural engineering projects.

The ideal foundation for a large structure—whether it be a suspension bridge tower, a steel skyscraper or a concrete dam—is sound bedrock. However, the geology underlying construction sites does not always provide such ideal conditions, and bedrock is often beyond easy reach. Furthermore, bedrock is sometimes inadequate as a foundation because of inherent defects. Therefore engineers have learned to work with the hand that nature deals them. The Romans developed techniques for sinking piles into soft riverbeds, so that bridge piers rested on foundations firm and deep enough to resist the settling and scouring actions that must have led to the collapse of many an earlier bridge. The master builders of Gothic cathedrals directed the laying of broad-based foundations to provide proper footings for their edifices, lest the masonry walls crack because of uneven movement in the ground. In more recent times, engineers of tall buildings have learned to erect them over broad mats or rafts at depths that ensure sufficient buoyancy that the ground floor of the completed structure matches up with the street and does not sink over time. These and other schemes for building foundations that could not reach to bedrock have become a fundamental part of the art and science of civil engineering.

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Soil's Confounding Effects

For more than eight centuries now, however, the leaning Tower of Pisa has been an effective reminder that engineers do not always build on firm foundations. Other towers and buildings, such as the Guadalupe National Shrine in Mexico City, are also noticeably tilted; some reveal the telltale signs of differential settlement through cracked walls. Some prominent structures have settled more uniformly. The Washington Monument, begun in 1848, had settled almost six inches by the time its interrupted construction was completed in 1884, with a modified foundation. Settlement of the Palace of Fine Arts in Mexico City was more noticeable, for what was once its ground floor became its basement over time. Sometimes, nearby construction can affect long-standing structures. This happened to Trinity Church in Boston when ground across Copley Square was excavated to build the John Hancock Tower.

Some structures are actually built of soil, which is said to be civilization's oldest building material, and failures of earth dams were endemic through the 19th century and not unknown in the 20th. Teton Dam, a massive earth structure across the Teton River Canyon in southeastern Idaho, was built on volcanic rock that was unusually fractured. The dam failed in 1976, just six months after its completion, while its reservoir was being filled. Concrete dams have not been immune to soil problems, and the failure in 1928 of California's St. Francis Dam, located 45 miles northwest of Los Angeles, was traced to a defective foundation on rock—a fault and a landslide played roles in destroying the dam. The release of 12 billion gallons of water killed approximately 450 people. Explaining such failures, and obviating similar failures in future construction projects, requires an understanding of the nature and behavior of soils, especially under changing conditions of water content, consolidation and structural loading.

The Father of Soil Mechanics

The engineering science of soil mechanics, whose development was motivated by such problems, takes the solution of these problems as its challenge. It is generally agreed that its roots are in the work of the 18th-century French civil engineer Charles Augustin Coulomb, whose studies of friction forces gave engineers a rudimentary means to determine the steepness at which a pile of sand or an earth embankment would become unstable and result in a landslide. Throughout the 19th century, however, few mechanical properties other than the so-called angle of repose and bearing pressure were measured for soils, and by the end of the century Coulomb's work was discounted by working engineers. Such important soil variables as density, water content and compressibility remained to be considered, and they would not be in any rational way until an Austrian engineer named Terzaghi found himself assigned to Turkey to lecture on construction and foundations. Fortunately, that assignment, and the time for experiment and reflection that it provided, came after the engineer had already gained invaluable experience in the field. The story of this engineer's life and career, as recounted by his students and colleagues, sometimes takes on mythic proportions, something Terzaghi himself seems not to have discouraged.

Figure 1. Karl Terzaghi, the founder of the engineering science of soil mechanics. (Drawing by Eugene Montgomery, courtesy of Duke University.)

Karl Terzaghi was born in Prague in 1883, when it was the capital of the Austrian province of Bohemia. Being descended from a long line of Austrian army officers, he was naturally sent to military school. But the military held no attraction for him, and he went on to attend the Technical University in Graz, where he acquired the dueling scars that marked him for life. He graduated in 1904 with a degree in mechanical engineering, a field that would never excite him, but while in school he also was attracted to geology and showed promise as a writer. After further studies that concentrated on geological topics, Terzaghi began working for a Viennese engineering firm that specialized in reinforced concrete structures and hydroelectric power, which naturally involved the construction of dams. After three years working mainly in the Swiss Alps, Terzaghi became restless with his assigned work, and in time he found himself in charge of the geologic and hydrographic survey for a hydroelectric power project proposed in the hinterland near the Adriatic Coast of Croatia.

Terzaghi then secluded himself in the Alps to work on a long paper reporting on his Croatian survey. While in the Alps, Terzaghi heard from a friend in Leningrad of the stoppage of work on a monumental structure in that city because buildings surrounding the excavation had begun to settle and crack. Terzaghi offered to take charge of the project for the contractor, and in a short time had everything under control. Afterwards, he participated in the design and construction of other projects in northwest Russia, and he became increasingly aware of the great discrepancy between the state of the art of reinforced concrete design, which was quantitative, and that of foundation design, which was not. He began to think that the problems of foundations and earthwork were attributable "only to gaps in our knowledge of the relationship between geological conditions and engineering consequences." The gaps could be closed, he believed, by failure analysis—that is, "by collecting and digesting case records in which each event, such as a foundation failure or the failure of an earth dam, was meticulously correlated with the geological conditions at the site."

Not surprisingly, Terzaghi was not the only person in the world struck by the paucity of understanding of soil as an engineering material. In the United States, in particular, the Reclamation Service was involved in the construction of a large number of dams and irrigation systems under widely varying geologic conditions, and the director of the service agreed with Terzaghi that this was a rare opportunity to take part in a large-scale experiment that might provide much needed insight. Thus Terzaghi spent two years in the western states observing and collecting data. But once back in Europe, he became discouraged when his attempts to make sense of it led to naught.

Terzaghi Joins Academia

World War I drew Terzaghi into the Austrian Army, but in 1916 he found himself ordered to

Figure 2. Karl Terzaghi *(right)* and Ralph Peck at the third international soils conference in Switzerland in 1953. (Photograph courtesy of Ralph Peck.)

accept an assignment as a professor of foundations and roads in Constantinople, at the Imperial School of Engineers that one of his former teachers was reorganizing. According to Terzaghi, "I myself felt no urge whatsoever to teach because I was too deeply pre-occupied with my own ignorance." Nevertheless, the assignment gave him an opportunity to reconsider his data from America, and he realized the cause of his former impasse: At that time, soils were classified in strictly geological terms—coarse sand, fine sand, soft clay, stiff clay and the like—with each such designation including soils of widely different engineering properties. Terzaghi concluded that what was needed was a means of measuring quantitatively a variety of material properties that would distinguish soils in a unique way and that would, not incidentally, enable engineers to predict by calculation such phenomena as bearing strength and settlement rate.

Such realizations were not unique to Terzaghi at the time. When the Panama Canal was being dug, landslides in the famed Culebra Cut through the continental divide had provided further dramatic and incontrovertible warnings that engineers "were overstepping the limits of our ability to predict the consequences of our actions." The situation in Panama, in addition to continuing dam failures and building settlings, had led the American Society of Civil Engineers in 1913 to appoint a committee to look into such matters. This committee stressed "the importance of expressing the properties of soils by numerical values." Similar realizations came in Sweden, where railway work was accompanied by catastrophic landslides, and in Germany, where massive retaining walls were moving in unacceptable ways. But Terzaghi was to have the key theoretical insights.

After the war, Terzaghi remained in Constantinople as a lecturer at Robert College, then often referred to as the American Robert College and now known as Bogaziçi University. At Robert, he taught mechanical-engineering courses while pursuing his research into soils. Then, in a reflective mood in 1918, he "wrote down in one day and on one sheet of paper" a program of experiments that he expected would take two or three years. In fact, his efforts would extend over seven years. Working alone, without access to the contemporary literature, and using equipment that included cigar boxes and parts scrounged together from the college dump, he came slowly to understand the mechanics of soils. In 1920 he published a "first report" on his work, under the Americanized name of Dr. Charles Terzaghi, in *Engineering News-Record*. An accompanying editorial, "Research in Soil Mechanics," not only coined a name for the new field but also declared "the problem presented by earth as an engineering material" to be "so important that it deserves to be ranked as the outstanding research problem in civil engineering." The editorial, which also described other approaches to the problem, concluded that Terzaghi's fundamental research into determining "the mere facts of earth action" heralded "the opening of an avenue of progress which promises to lead on toward more definite knowledge of earth."

Terzaghi continued his work and developed a model describing how water carried in microscopic voids gradually transferred the loads imposed on it to the grain structure of clays. He first presented a mathematical model for this consolidation process in a 1923 article that received little attention. However, when he presented a paper on the topic at the First International Conference on Applied Mechanics, held in Delft, Holland, in 1924, "the response was instantaneous and enthusiastic." Terzaghi's 1925 book, *Erdbaumechanik auf bodenphysikalischer Grundlage*, led to his being offered a visiting lectureship at the Massachusetts Institute of Technology, which he accepted. Later, looking back on his seminal contributions, Terzaghi confessed that he "had only laid the foundation: the edifice remained to be created." He would also attribute his success to the fact that he "had the urge, the opportunity, and the patience in addition to the qualifications required for engineering the revolution which had already become inevitable."

With MIT as a base of operations, Terzaghi began to consult on a wide variety of earthwork and foundation problems, and he incorporated his practical experience into his teaching of soil mechanics. In 1929, Terzaghi accepted a professorship at the Technical University in Vienna and thus returned to Europe. Among the group of disciples that Terzaghi had left in America was Arthur Casagrande, a native Austrian and graduate of the Technical University in Vienna, who went from studying under Terzaghi at MIT to becoming an assistant professor in the Graduate School of Engineering at Harvard University. In the ensuing years, it became increasingly clear to Casagrande and to others that the growing number of soil-mechanics specialists, let alone practicing engineers, were having difficulty in keeping up with the rapid developments in approaches to problems in earth and foundation engineering, and there developed a growing interest in holding a conference on the subject. The conference organized by Casagrande, which was also a means to bring Terzaghi back to the U.S. for the spring of 1936, proved to be a model of individual and institutional initiative.

Harvard University accepted the suggestion that it sponsor, as an official part of its tercentenary celebration, the International Conference on Soil Mechanics and Foundation Engineering, to be held in June 1936. The university would not only finance the conference but also provide living quarters and other amenities for the attendees. A registration fee of five dollars, raised to ten for late registrants, included the *Proceedings*, the third volume of which contained a record of the conference and a detailed treasurer's report. The conference drew a total membership of 206, with another 181 absentee members being sent the *Proceedings*. The members in attendance were welcomed to the first official event of Harvard's tercentenary year by President James B. Conant, who proceeded to review the history and development of the university. The address of the president of the conference was delivered not by the Charles Terzaghi whose articles had graced the pages of *Engineering News-Record*, but by a lionized "Karl von Terzaghi, Professor at the Technische Hochschule in Vienna," and the *Proceedings* contain about a half dozen papers by "Dr. Karl v. Terzaghi."

The distinguished Terzaghi returned to Vienna in the fall and attended to his expanding consulting practice. With growing unrest in Europe, however, he came back to the United States in the fall of 1938, as Visiting Lecturer in Soil Mechanics at Harvard. That same fall, Terzaghi was invited to lecture in Chicago, and he chose the title "The Dangers of Tunneling in Soft Clays Beneath Large Cities." His remarks were equally interesting to the city's Department of Subways and Traction, which had undertaken to build a subway, and the State Street Property Owners' Association, which worried about the consequences for nearby structures, and both groups wished to retain Terzaghi

Figure 3. Karl Terzaghi *(left)* and Ralph Peck at Lake Maracaibo, Venezuela in 1956. (Photograph courtesy of Ralph Peck.)

as a consultant. He eventually chose to consult for the city, which agreed to his fee of an unprecedented $100 a day and to the stipulation that a laboratory be set up and supervised by the individual of Terzaghi's choice and under his direct supervision. Who that assistant was to be was an interesting accident of the times.

A Fortuitous Collaboration

Ralph Peck, almost 30 years younger than Terzaghi, had a Doctor of Civil Engineering degree from Rensselaer Polytechnic Institute, with an emphasis on structures and mathematics. His thesis related to the stiffness of suspension bridges, a topic inspired by the work of the prominent bridge engineer David Steinman, who was supportive of Peck's efforts. After receiving his degree in 1937, Peck attended the Detailing School of the American Bridge Company, in whose drafting room he afterwards worked. When bridge work slowed down and Peck found himself laid off, however, he looked for a job wherever he could find one. The dean at the Armour (later Illinois) Institute of Technology in Chicago told Peck there were no openings there in structures, but that if he could study either hydraulics, at Iowa, or soil mechanics, at Harvard, he would have a position at Armour. A job offer from the bridge firm of Waddell & Hardesty came shortly thereafter, but by that time Peck had determined to study soils and had finalized plans to go to Harvard.

As a nondegree student, Peck was able to join courses in the middle of the semester and took an unorthodox route to learning soil mechanics. He gained laboratory experience running consolidation tests and was sitting in on a course in statistics when Terzaghi needed someone to help him with English terminology in that field for his book in progress, *Theoretical Soil Mechanics*. Later, when Terzaghi was asked whom he wished to oversee the soil mechanics laboratory for the Chicago Subway project, Casagrande's suggestion of Peck was immediately taken. The three-year project, a milestone in the development of the practical application of soil mechanics, was interrupted by the consequences of Pearl Harbor. Afterwards, his work on the Chicago Subway project led to Peck's association not with Armour but with the University of Illinois, in Urbana, where he would spend a large part of his distinguished career.

In the meantime, Terzaghi was continuing to work on his book manuscript, and Peck became involved in reviewing it. His help was acknowledged in the preface to *Theoretical Soil Mechanics*, which appeared in 1943 with the dedication, "To Harvard University, in appreciation of its liberal encouragement of the pursuit of knowledge." Even before that book was published, Peck had begun to suggest to Terzaghi that he work on a second volume, which would serve as an undergraduate textbook and would include applied aspects of soil mechanics. Terzaghi asked Peck to coauthor such a work, which would appear in 1948 as *Soil Mechanics in Engineering Practice* and become a seminal text.

With his continuing teaching, publishing and worldwide consulting, Terzaghi's reputation was secure. In 1946 he had become Professor of the Practice of Civil Engineering, a title said to have been created by Harvard especially for him. He began to turn down consulting jobs that did not present a fresh challenge, and thus he began to work increasingly in British Columbia, where the geology and foundation conditions were unusually complex. The Coast Mountains may also have evoked memories of his early work in Europe.

Among the projects that occupied Terzaghi's last years were a series of dams in British Columbia. According to Peck, one of these projects, Mission Dam, was "so complex and difficult from a geotechnical point of view that many engineers had considered it to be infeasible." Terzaghi died in 1963, and two years later, at a memorial service at the Sixth International Conference on Soil Mechanics and Foundation Engineering in Montreal, Mission Dam was renamed Terzaghi Dam. Such an honor is rare for any engineer, but few areas of modern engineering are as inextricably linked with a single individual as soil mechanics is with Terzaghi. Indeed, the field itself stands as a memorial to his pioneering work, which so defined it.

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