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1. Introduction

1.1 SOIL MECHANICS AND RELATED FIELDS

Soil mechanics is one of the engineering disciplines that deal with soils as an engineering material. Since ancient ages, engineers have been handling soils as an engineering material for various construction projects. Construction of the Egyptian pyramids, Mesopotamian ziggurats, Roman aqueducts, and China's Great Wall are a few of such magnificent historical achievements. However, those ancient projects were mostly accomplished by accumulated experiences of ancient engineers. During the eighteenth and nineteenth centuries, some modern engineering theories were employed in this field, following the development of Newtonian mechanics. Coulomb's and Rankine's lateral earth pressure theories (Chapter 12) are some examples of such theories.

The modern era of soil mechanics had to wait until 1925, when Dr. Karl von Terzaghi published a book called *Erdbaumechanik* (1925). Especially, his thennew concept of "effective stress," which deals with interaction with pore water, has revolutionized the mechanics of soils. The development of modern soil mechanics is due to his great contribution. He is now regarded as the father of modern soil mechanics.

Related terminologies of soil mechanics are foundation engineering, geotechnical engineering, and geoenvironmental engineering. Foundation engineering is the field of designing safe foundations, including building footings and retaining structures, and the construction of earth structures such as embankments, earth and rockfill dams, safe earth slopes, etc., based on the knowledge of soil mechanics. Thus, the discipline has been called soil mechanics and foundation engineering for many years. The new term, geotechnical engineering, was coined around 1970 to merge rock mechanics into soil mechanics and foundation engineering, and it is the most popularly used terminology in this field at present. In the 1980s, environmentally related geotechnical engineering became a great engineering concern, and the term geoenvironmental engineering was created. This includes the design and construction of solid- and liquid-waste containment facilities and any other environmentally related geotechnical engineering problems.

1.2 BIOGRAPHY OF DR. KARL VON TERZAGHI

Dr. Karl von Terzaghi (Figure 1.1), the father of modern soil mechanics, was born in Prague, Austria, in 1883. At the age of 10, Terzaghi was sent to a military boarding school. He developed an interest in astronomy and geography. He entered the Technical University in Graz to study mechanical engineering in 1900. He graduated with honors in 1904. Terzaghi then fulfilled a compulsory year-long military service.



FIGURE 1.1 Karl von Terzaghi at age 43.

He returned to the university for 1 year after this and combined the study of geology with courses on subjects such as highway and railway engineering.

His first job was as a junior design engineer for a firm in Vienna. The firm was becoming more involved in the relatively new field of hydroelectric power generation, and Karl became involved in the geological problems the firm faced. He embarked on an ambitious and challenging project to construct a hydroelectric dam in Croatia and an even more chaotic project in St. Petersburg, Russia. During 6 months in Russia, he developed some novel graphical methods for the design of industrial tanks, which he submitted as a thesis for his PhD at the university. His growing list of achievements began to open more opportunities to him. He then resolved to go to the United States in 1912.

There, he undertook an engineering tour of major dam construction sites on the West Coast. This was no ordinary tour, but rather was his opportunity to gather reports and firsthand knowledge of the problems of many different projects, and he used it to the fullest before returning to Austria in December 1913. When World War I broke out, he found himself drafted into the army. He faced combat in Serbia and witnessed the fall of Belgrade. After a short stint managing an airfield, he became a professor in the Royal Ottoman College of Engineering in Istanbul (now Istanbul Technical University). He began a very productive period, in which he began his lifelong work of bringing true engineering understanding to the subject of soil as an engineering material. He set up a laboratory for measurements of the force on retaining walls. The results were first published in English in 1919 and were quickly recognized as an important new contribution to the scientific understanding of the fundamental behavior of soils.

At the end of the war, he was forced to resign his post at the university, but managed to find a new post at Robert College in Istanbul. This time he studied various experimental and quantitative aspects of the permeability of soils and was able to work out some theories to explain the observations. In 1925, he published much of this in *Erdbaumechanik*, which revolutionized the field to great acclaim and resulted in the offer of a position from the Massachusetts Institute of Technology (MIT), which he immediately accepted.

One of his first tasks in the United States was to bring his work to the attention of engineers. He entered a new phase of prolific publication, and a rapidly growing and lucrative involvement as an engineering consultant on many large-scale projects.

In 1928, Terzaghi was determined to return to Europe. He accepted a chair at the Vienna Technische Hochschule in the winter of 1929. Using Austria as his base, he traveled ceaselessly throughout Europe, consulting and lecturing, and making new professional contacts and collaborations. Terzaghi then returned to America, where he gave a plenary lecture at the First International Conference on Soil Mechanics and Foundation Engineering at Harvard University in 1936. He served as the first president of the International Society of Soil Mechanics and Foundation Engineering from 1936 to 1957.

He made a lecture tour of many other universities but discovered that prospects for employment were dim. He returned to Vienna in November 1936. There, he was caught up in a nasty professional and political controversy. He escaped from Vienna frequently by extended consulting trips to major construction projects in England, Italy, France, Algeria, and Latvia, adding greatly to his store of practical engineering experience.

In 1938, Terzaghi immigrated to the United States and took up a post at Harvard University. Before the end of the war, he consulted on the Chicago subway system and the Newport News shipways construction, among others. He became an American citizen in March 1943. He remained as a part-timer at Harvard University until his mandatory retirement in 1953 at the age of 70. In July of the next year, he became the chairman of the consulting board for the construction of the Aswan High Dam. He resigned this post in 1959 after coming into conflict with the Russian engineers in charge of the project, but continued to consult on various hydroelectric projects, especially in British Columbia. He died in 1963.

In honor of his great contribution in the field, the American Society of Civil Engineers (ASCE) established the Karl Terzaghi Award in 1960 to be awarded to an “author of outstanding contributions to knowledge in the fields of soil mechanics, subsurface and earthwork engineering, and subsurface and earthwork construction,” and the Terzaghi lectures are delivered and published annually as a highest honor in the field (abbreviated and modified from Wikipedia).

Goodman (1999) provides a detailed biography of Dr. Karl von Terzaghi that is strongly recommended for all geotechnical engineers and geologists to learn more about his great contributions and many lessons on professional practice.

His contribution is throughout this book, including effective stress, consolidation, shear strength, and bearing capacity theory.

1.3 UNIQUENESS OF SOILS

As this book shows, soil is a very unique material and complex in nature. The unique characteristics of soils are as follows:

1. It is not a solid, continuous material, but rather is composed of three different constituents: solid (grain), water, and air, and is thus an aggregated material.
2. Particle sizes have significant influence on soil behavior from granular soil to clay.
3. The amount of water also plays a very important role in soil behavior.
4. Its stress-strain relation is not linear from the small strain levels.
5. Its pore spaces possess the capability of water flow.
6. It has time-dependent characteristics; that is, it is susceptible to creep.
7. It swells when wetted or shrinks when dried.
8. It is an anisotropic material due to the particle shapes and the depositional direction under gravity.
9. It is also spatially nonhomogeneous.

To handle this unique nature, the discipline utilizes many different areas of mechanics. For the various phases, it uses solid mechanics as well as discrete mechanics. The water flow characteristics are explained by knowledge of fluid mechanics such as Darcy's law and Bernoulli's law. Physicochemical knowledge is required to understand swell and shrinkage characteristics. Understanding its anisotropic characteristics requires a high level of knowledge in mechanics and material science. Some statistical approaches are also needed to treat the nonhomogeneity of soils.

As briefly seen earlier, soil is a very unique material, and its engineering properties vary a lot depending on the particle sizes, origins, and many other factors. Their constitutive models are not as simple as Hooke's law, which is used in some other materials.

1.4 APPROACHES TO SOIL MECHANICS PROBLEMS

Complexity and spatial variation of soil make the field observation and laboratory testing very significant. Field observation ranges from geological study of the site to soil sampling and sometimes in-situ testing of properties, such as well tests for permeability, vane shear tests for strength determination, etc. Sampled specimens are brought back to laboratories for various physical and mechanical tests. The former includes the grain size test, Atterberg limits tests, specific gravity test, etc., and the latter includes a compaction test, permeability test, consolidation test, and various shear strength tests.

Based on field observations and laboratory test data, geotechnical engineers classify soils, determine design properties, and design safe foundations and earth structures, by fully utilizing modern soil mechanics knowledge and foundation engineering concepts. Construction companies carry out construction of the project according

to specifications made by design engineers. Usually, design engineers monitor construction practices carefully for proper execution.

The last stage is field monitoring of the performance of earth structures. At present, large construction projects always come with instrumentation and performance monitoring. Simple or complex theories are available in most cases. However, those are not always perfect due to complexity of soils and variations in material properties. Thus, the monitoring and reevaluation of design based on the feedback of the data are very crucial for the success of projects.

1.5 EXAMPLES OF SOIL MECHANICS PROBLEMS

Engineers have to deal with many challenging soil mechanics problems even at present, as well as in the past. A few historical and interesting cases are presented in the following subsections.

1.5.1 Leaning Tower of Pisa

This famous building illustrates historical soil mechanics problems. The 56 m high bell tower at Pisa, Italy, leans about 3.97° or 3.9 m at top toward the south. The construction of the tower started in 1173 and was completed in 1372. It was reported that the tower started to sink unevenly after the construction progressed to the third floor in 1178 and more floors were built up to accommodate for the tilt.

The lean is obviously due to uneven settlement of the foundation soil. This time-dependent settlement phenomenon is called consolidation settlement of clay and is discussed later in this book. In March 1990, the tower was closed to the public due to the possibility of collapse in the near future. Engineering remediation procedures were discussed to stop further leaning. An early attempt was made to put heavy load (800 metric tons of lead counterweight) on the north side of the tower foundation to compensate for the larger settlement on the south. A more drastic measure was taken later to extract soil mass ($38 m^3$) under the north side of the foundation soil by angled auger holes so that the north side experienced extra settlement. In December 2001, the tower was reopened to the public and has been declared stable for at least another 300 years (Figures 1.2 and 1.3).

1.5.2 Sinking of Kansai International Airport

The first-phase construction of Kansai International Airport, a man-made island (4.5 km long and 1.1 km wide) near Osaka, Japan, began in 1987, and the airport became operational in 1994. It was an amazingly fast-paced construction for a project of this magnitude. The massive earth filling at an average water depth of 12 m on Osaka Bay required 208,000,000 m^3 of reclaimed soil and rock (82 times the volume of the Great Pyramid of Giza). The filling materials were brought from excavations of three mountains nearby. Geotechnical engineers anticipated quite a large consolidation settlement due to this massive fill over a large area on soft bay foundation soil. Settlement, which immediately started, was carefully monitored, and results were compared with computed values. It sank 50 cm in 1994; settlement



FIGURE 1.2 Leaning tower of Pisa.



FIGURE 1.3 Lead counterweight.

was reduced to 20 cm in 1999, and was 9 cm in 2006. Originally, engineers estimated 12 m total settlement in 50 years, but, in fact, it had already settled 11.5 m by 2001. Because of anticipated uneven ground settlement, the terminal building was equipped with jacks in each column so that uneven settlement could be adjusted not to have extra stress on individual columns. It is still sinking.



FIGURE 1.4 Kansai International Airport during phase II construction in 2002. (Photo courtesy of Kansai International Airport Land Development Co.)

Amazingly, the phase II runway, the second island on deeper water, has been constructed (Figure 1.4 in 2002 and the cover page picture in 2003) and opened to operation in 2007. This is a magnificent mega-construction project in recent years with very challenging geotechnical engineering problems.

1.5.3 Liquefaction-Sand Becomes Liquid during Earthquake

Can you believe that soil transforms into liquid? Yes, it does. During Japan's 1964 Niigata earthquake with a Richter magnitude of 7.5, apartment buildings lost their foundation support and sank and tilted (Figure 1.5). Foundation soil was transformed into viscous liquid due to earthquake vibration. A similar phenomenon was also observed in the Alaska

earthquake that occurred in March 1964. Liquefied soil triggered massive landslides in Anchorage. This phenomenon is called soil liquefaction. Soil liquefaction describes the behavior of soils that,



FIGURE 1.5 Building tilt and settlement due to liquefaction during the 1964 Niigata earthquake.

when cyclically loaded, suddenly go from a solid state to a liquefied state or have the consistency of a heavy liquid and cannot support the foundation load any longer. Liquefaction is more likely to occur in loose to medium dense, saturated, granular soils with poor drainage, such as fine sand or silty sand. During loading, usually cyclic undrained loading-for example, earthquake loading-loose sand tends to decrease in volume, which produces an increase in its pore water pressure and consequently a decrease in shear strength-that is, reduction in effective stress (Chapter 7).

Liquefaction is one of the major geotechnical engineering problems during earthquakes. It causes the settlement and tilting of buildings, catastrophic slope failures, and massive lateral movement of the ground. Although this topic is not covered in this book, it is one of the major topics in the advanced soil mechanics field, soil dynamics, or earthquake engineering.

1. REFERENCES

Goodman, R. E. (1999), Karl Terzaghi-The Engineer as Artist, ASCE Press, Alexandria, VA, 340 pp.

Terzaghi, K. (1925), Erdbaumechanik, Franz Deuticke.