Chapter 0 General Introduction

Soil is an admixture of organic matter, minerals, gases, liquids, and organisms. Due to its variable composition, soil can be categorized into different types. As a natural composite, its behavior is far more complex than those artificial materials used in civil engineering, i.e., steel, concrete, brick.

As almost all geotechnical structures rest on soil, the role of soil under the action of various loads during construction, post-construction, as well as serviceability stage has always been a concern. Soil mechanics is one of the disciplines to help engineers to master the behavior of soil in practical engineering.

Soil mechanics mainly deals with two kinds of problems: 1) The deformation problem. The newly-built structures not only alter the original state of soil, but also induce stress increment in soil. Both uniform and differential settlements affect the functionality of structures. More importantly, if the settlement exceeds a certain value, it results in the tilting or cracking of the structures; 2) The strength problem. When the induced stress in soil exceeds its resistance (strength), the soil becomes unstable and the collapse of structures occurs.

Moreover, the water within soil causes the two problems mentioned above more complex.

When the external load is applied, the induced excess pore pressure generates and shares the load with the soil skeleton.

As time elapsed, the excess pore pressure decease as the water is being squeezed out of the void. As the squeezing process is time consuming, which is significantly true for soil with low permeability, the settlement in such kind of soil may last for several years or even several decades. This phenomenon is known as consolidation.

According to Terzaghi's theory, the load bears by the soil skeleton (effective stress) is not a constant. It increases with the decrease of pore pressure. As deformation and failure of soils are governed by the effective stress acting on the soil skeleton, this may explain why certain structure keeps settling during a long period of time.

When there is head difference, water flow through the interconnected space in the soil. The flow of water through the soil mass may results in two effects: 1) the interconnected forces get weakened as the water starts excreting pressure and as a result of which the cohesive force between the particles become weaker; 2) the flow of water may impose the additional stress (viscous drag) on the particles, which may increase or decrease the stress undertaken by the skeleton depending on the direction of flow. These two effects further influence the deformation and stability of soil.

0.1 Typical characteristics of soil

As the soil is the masterpiece of nature, it is a very unique and complex. The characteristics of soil are as follows:

- Soil is formed from the weathering of rocks. The discrete aggregates are joined by cohesive force (electrostatic force, cementing (chemical bonds), apparent cohesion) and interparticle friction force. Comparing with rocks, it deforms easily and has low strength (Unlike the diagenesis, the formation of soil does not subject to compaction, dehydration, cementation, hardening)
- Practically, soil is mainly made up of mineral particles, organic materials, air, water and living organisms-all of which interact slowly yet constantly. Accordingly, it is spatially nonhomogeneous. For simplicity, soil is skimpily regarded as a three-phrase composite with soil particles form the skeleton. The void part is filled with water and air. If the void is filled only with water or air, we it saturated or dry soil correspondingly
- Particle sizes have significant influence on soil behavior. Normally, the finer the particles, the better compaction of soil and accordingly the higher strength of soil
- Comparing with other civil engineering materials (concrete, steel, wood). Water is a distinctive phase (component) in rock and soil, which plays a very important role in their behavior
- The stress-strain is no-linear in the hypothesis of infinitesimal deformation. For cohesionless soil, its behavior depends on the compactness. The deformation of soil has time-dependent feature, consolidation (dissipation of

excess pore pressure) and secondary consolidation (the continued deformation of the soil structure after excess pore pressure has dissipated as certain particles will move to new position under the action of shear process)

- It is an anisotropic composite due to particles shapes and depositional direction under the action of gravity
- Under certain geological environment, soil may possess special characteristics which we call special soils in practical engineering like collapsible loess, expansive or swelling soils, frozen soil, soft soil.

To handle these characteristics, only with mechanics of materials is far from enough. For example, to deal the water flow in the interconnected space of soil, we need the knowledge concerning fluid mechanics such Darcy's law. To describe the no-linear behavior, limit analysis involved in plastic theory is necessary. Full understanding the deformation mechanisms requires sophisticated knowledge in mechanics and materials science.

0.2 Fields related to soil

Soil is widely used in civil engineering. Many engineering constructions, including dam, embankment, tunnel, canal and waterway, foundations for bridge, roads, buildings, solid waste disposal system, depend on the geological conditions of the site and mechanical behavior of the soil.

- Hydraulic engineering: In hydraulic engineering, the most common structures is dam. It is a barrier that stops or restricts the flow of surface water. The reservoir formed by dam can be used to collect the water. At ancient ages, the dams were built on pervious foundation and accordingly, the water could flow through the interconnected void space from high hydraulic head to low hydraulic head (seepage phenomena). As we know, the flowing water exerts a drag on the soil particles in the direction of its motion. The force is proportional to the flow velocity. If the force is large enough, namely the flowing rate is high enough, the water has the capacity to displace the solid particles. In this case, the foundation will be gradually eroded and pipe-shaped channels will form. If no measures were taken, the dam may fail due to piping failure. We will detail this phenomenon in Chapter 2
- Foundation engineering Foundation is the bridge between the top structure and

the ground (base). It ultimately transmits the load of structures to soil. Foundations are generally considered either shallow or deep. The newly built structure not only disturbed the origin stress state within the origin soil layers, it also induces the additional stress in soil layers (Chapter 3). The additional stress results in additional settlement, which will affect the functionality of the structures (Chapter 4). Moreover, the bearing capacity, which is the maximum pressure that the soil can support at foundation level without failure, is a key design parameters for foundation design (Chapter 8).

- Pavement engineering Pavement engineering is a branch of civil engineering that uses engineering techniques to design and maintain flexible (asphalt) and rigid (concrete) pavements. Flexible pavements depend more on the subgrade soil for transmitting the traffic loads. Problems peculiar to the design of pavements are the effect of repetitive loading, swelling and shrinkage of sub-soil and frost action. Consideration of these and other factors in the efficient design of a pavement is a must and one cannot do without the knowledge of soil mechanics.
- Underground Space Engineering With the development of urbanization, the construction underground becomes unavoidable. For example, the construction of underground tunnels, drainage structures, pipe lines, passageways, underground spaces (garage, shopping mall). During the excavation, the stability of soil mass around or the slop of the pit should be ensured. Many a times, temporary or permanent support are necessary. The effect of underground water should be also taken into account. Lowing the water before excavation will induce the additional stress, which will further induce the additional subsidence of the buildings around. Water inrush is one of the most important causes of foundation pit accidents. The removal of overlying soil disturbs the balance between the pressure of confined water and weight of soil layers. Therefore, the remaining thin layer have a risk of being collapsed, and the pit will be flooded.
- Slope Engineering The field of slope engineering encompasses slope stability analysis and design, movement monitoring, and slope safety management and

maintenance. Engineers in this field are concerned with landslides and other gravity-stimulated mass movements. The nature of the soil forming the slope, and the slope geometry, will dictate the nature of potential slope failure mechanisms and so the appropriate means of analysis and safety factors. Appropriate selection of analysis parameters, such as undrained shear strength and the friction angle and, if present, a cohesion intercept (c) of granular soils, is critical to the slope assessment process. To design of retaining structure like gravity retaining wall, anti-slide pile, prestressed anchor-cable and lattice beam, soil nail wall, the lateral stress exerted on these structures should be correctly evaluated (Chapter 7).

Apart from above mention related fields, other fields like sea-cross bridge or tunnel, landfill (garbage dump) design, high fill embankment or foundation also involve numerous problems related to soil.

0.3 Typical engineering problems related to soil

During the history of human development, soil has been considered as main engineering material for various construction projects. However, those ancient projects were mostly accomplished by accumulated experiences of ancient engineers. Due to the lack of full insights of the behavior of soil in site, the testing devices and the advanced design concepts, several engineering problems occurred.

- Foundation soil failure – the Transcona grain elevator The Transcona grain elevator was built by the Canadian Pacific Railway Company near Winnipeg in 1913. The warehouse was designed to store grain from the city of Winnipeg and the wider area. The Transcona grain elevator is a reinforced concrete structure consisting of an engine room and a grain storage area containing five rows of 13 containers. The construction is based on a reinforced concrete slab measuring 23.50 m x 59.50 m, with an upper and lower reinforced concrete slab 60cm thick between which there is a space for emptying. Such a foundation structure with two slabs and transverse and longitudinal stiffeners (walls) is a very rigid foundation structure. The accident took place during the filling process. When the tanks were filled up to 87.5%, large settlements of the storage building were noticed. Within one hour, the settlement increased to 300mm with a slope to the west, and within 24 hours the foundation soil collapsed, and the structure tilted about 27°. According the thorough failure investigation after the incident, researchers found that no detailed geotechnical investigation and testing was conducted before works began. Additional exploratory boreholes showed that the soil layers under the foundation are not uniform, which were assumed homogeneous during design. The load from the structure under the foundation also affected the lower, softer layer of clay, which has a much lower load-bearing capacity. According to today's investigations, when the lower layer with the lower parameters is taken into account, the permissible load is far lower than the actual load.

- Leaning of structure – Tower of Pisa (Italy) and Tiger Hill Tower (China). The Leaning Tower of Pisa is the landmark of the cathedral of the Italian city of Pisa. It is known worldwide for its nearly 4° lean and the famous free fall test carried out by Galileo Galilei. The height of the tower is 55.86 meters from the ground on the low side and 56.67 meters on the high side. The tower began to lean during construction in the 12th century, and it worsened through the completion of construction in the 14th century. The lean is obviously due to uneven settlement of the foundation soil. Site investigation showed that under the foundation of the tower are mainly silt and clay. These soils are typical impervious soils with very low permeability. Upon loading, the excessive pore pressure is hard to dissipate and the settlement of the structure will last long time. The Yunyan Temple (the nicknamed is Leaning Tower of China) was founded in 907CE (Common Era) and was last rebuilt in 1871. Its height is 47 m. The pagoda has seven stories and is octagonal in plan, and was built with a masonry structure designed to imitate wooden-structured pagodas prevalent at the time. Now the top and bottom of the tower vary by 2.32 m (leans roughly 3°). Site investigation show that the foundation of the pagoda is originally half rock and the other half is on soil, which result in the lean.
- The 1972 Hongkong landslide. A series of major landslides occurred in Hong Kong in June 1972. First there was the landslide on Po Shan Road, which took out several houses, killing 67 in the process. Later in the day, a landslide occurred at Sau Mau Ping, which occurred above a squatter area and was

almost instantaneous, burying the people there alive before they had time to react. This landslide led to 71 deaths. Investigation showed that many factors contribute to landslides: 1) One major contributing factor is erosion. which reduce the strength of surficial soil and rock; 2) special soil/rock composition. Granitic rock tends to be much more susceptible to Hong Kong's weather conditions. The weathering product of granitic rock is granite residual soil, which has poor strength; 3) Meteorological events. During June of 1972, rainfall in the Po Shan area of Hong Kong was the heaviest it had ever been that year. Rainwater infiltration further reduces the strength of the residual soil.

- Piping and hydraulic fracturing caused earthen dam failure – Teton Dam. The Teton Dam was an earthen dam on the Teton River in Idaho, United States. It has 90m high and 1000m wide, finished in 1972-1975. It suffered a catastrophic failure on June 5, 1976, as it was filling for the first time. The collapse of the dam resulted in the deaths of 11 people and 13,000 cattle. The dam cost about $100 million to build and the federal government paid over $300 million in claims related to its failure. Total damage estimates have ranged up to $2 billion. The dam has not been rebuilt. An investigation identified that two mechanisms may be the cause for the failure: 1) piping, the flow of water under highly erodible and unprotected fill, through joints in unsealed rock beneath the grout cap and development of an erosion tunnel; 2) hydraulic fracturing. The cracking of core material caused by differential strains or hydraulic fracturing
- Liquefaction – Sand become liquid during earchquake. Liquefaction is more likely to occur in loose to medium dense, saturated, granular soils with poor drainage, such as fine sand or silty sand at or near the ground surface. Soils lose their strength in response to strong ground shaking. The shaking process rearrange and densify the particles and according, the water between particles is squeezed. The excessive pore pressure generate until the grains float and water is forced up to the surface through the easiest path it can find, often through the interconnected pores. The rising water takes silt and sand with it, forming sand boils or volcanos. In this case, soil completely lose its strength

and behaves as the liquid. Liquefaction occurring beneath buildings and other structures can cause major damage during earthquakes. Two representative examples are Niigata earthquak in 1964, Japan and Alaska earthquake in March 1964, USA.

0.4 Brief history of soil mechanics

The development of soil mechanics can be divided into three phases:

- Stage 1 (-1773) During the long history of human development, although soil has been applied as main engineering material for various construction projects, there is no "soil engineering" prior to18 century. Ancient projects were mostly accomplished by accumulated experiences of ancient engineers. The typical ones are Hanging Gardens of Babylon, parts of the Great Wall in China.
- Stage 2 (1773-1925) Classical soil mechanics began in 1773, the French physicist Charles-Augustin de Coulomb published his paper concerning the theory of earth pressure laid the theoretical foundation for the soil failure. He also combined his theory with that of Otto Mohr and finally established the classical Mohr-Coulomb theory. In 1857, the Scottish engineer William Rankine also proposed his own theory of earth pressure, which combines Coulomb's work forms the primary tools to quantify lateral stresses on retaining walls. These theories have been amended in the 20th century to take into account the influence of cohesion.
- Stage 3 (1725-1963) This period was marked by a series of important studies and publications related soil mechanics. In 1925, Dr. Karl von Terzaghi published a book called "Erdbaumechanik". Especially, he proposed a completely new concept of "effective stress," which deals with interaction with pore water, has revolutionized the mechanics of soils. Due to his great contribution, **he is now regarded as the father of modern soil mechanics**. Apart from Terzaghi's work, other scientists also contribute to soil mechanics, for example:
  - **H. Darcy** defined the hydraulic conductivity.
  - **J. Boussinesq** developed the theory of stress distribution.
  - **W. Fellenius, K. E. Petterson, A.N. Bishop, N. Janbu** has contribute

to the conventional methods of slope stability with limit equilibrium analysis theory.

- **M. Biot** extend Terzaghi's 1D consolidation theory to 3D.
- **Reynolds** demonstrated the phenomenon of dilation in the sand.
- **Atterberg** explained the consistency of cohesive soil by defining liquid, plastic and shrinkage limit

■ Stage 4 (1963-) With the construction of numerous key projects, the practical problems involved have greatly promoted the development of soil mechanics. Moreover, with the revolution of computational capacity, more complex working can be taking into account. The modern soil mechanics in this stage has the following characteristics:

- Owing to the development of in-situ observation, more and more researches have been conducted from a microscopic point of view.
- More and more constitute model taking into the corresponding deformation and damage mechanism are developed.
- Due to the heterogeneity of soil, several factors may affect the behavior of soil. To obtain more reliable evaluation, statically theory is introduced since 1970.
- Sophisticated field test devices with higher precision are developed and applied
- The laboratory testing environment is more and more approaching the real working conditions, which could provide designer and engineer with more valuable information, e.g., scaled model combining with vibration table or hypergravity centrifuge test
- The introduction of feedback analysis, which combines the advanced in-situ monitoring technique and design concepts, could help civil engineer better optimize the design
- The introduction artificial intelligent, big data analysis has further revolutionized the modern soil mechanics theory.

The modern soil mechanics can be divided into four main branches: theoretical soil mechanics, applied soil mechanics, experimental soil mechanics, computational soil mechanics. As the modern soil mechanics has a short history, many issues need to be further explored.

0.5 Brief biograph of Dr. Karl Von Terzaghi

Von Karl Terzaghi (1883, Prague–1963, U.S.A) was an Austrian mechanical engineer, geotechnical engineer, and geologist known as the "father of soil mechanics and geotechnical engineering". He founded the branch of civil engineering known as soil mechanics, which is the application of mechanics and hydraulics to engineering problems dealing with sediments and other unconsolidated accumulations of solid particles by mechanical and chemical disintegration of rocks regardless of whether or not they contain an admixture of organic constituents.

He studied mechanical engineering at the Technical University in Graz and graduated with honors in 1904. Terzaghi was awarded a doctorate in engineering by the same institution in 1911.

He served in the Austrian Air Force during World War I. When the war was over, he took a post (1918–1925) with Robert College, a U.S. institution, also in Istanbul. Much research had been done on foundations, earth pressure, and stability of slopes, but Terzaghi set out to organize the results and, through research, to provide unifying concepts. The results were published in his most noted work, **Erdbaumechanik**.

In 1925, he went to the United States and became a member of the faculty of the Massachusetts Institute of Technology (MIT), Cambridge. Apart from lecturing, doing research, and bringing his work to the attention of engineers, he also served as a consulting engineer for many construction projects.

In 1929, he returned to Europe and accepted a post at Vienna Technical University. In 1938, he returned to the United States and served as a professor of civil engineering at Harvard University from 1946 until his retirement in 1953. His consulting practice grew to encompass the world, including the chairmanship of the Board of Consultants of Egypt's Aswan High Dam project.

He died in 1963. In honor of his great contribution to the field, the American Society of Civil Engineers (ASCE) established the Karl Terzaghi Award in 1960.