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Chapter 3

A brief history of the development of geotechnical engineering

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This chapter traces the development of the craft and science of foundation engineering from early history to the recent past. The story is told of how Terzaghi struggled to couple engineering geology with the science of soil mechanics so as to provide the necessary rigour for modern geotechnical modelling and analysis. These lessons from the past are very important and a major aim of this manual is to provide the framework and knowledge necessary for sound geotechnical design and construction.

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3.1 Introduction

Foundation engineering is as old as the art of building and, like building, it developed largely on the basis of accumulated experience and empirical procedures. Because ground conditions vary so much from one locality to another, foundation practice varied widely. Moreover, the extrapolation of experience from one locality to another was fraught with uncertainty.

Parry (2004) describes how the ancient Egyptians learned from the foundation failure of the South Dahshur Pyramid. This was built during the reign of Pharaoh Snofru (2575–2551 BC) using a central core supported by a series of inclined buttress walls, as had become the tradition. The pyramid was founded on a clay layer. Large differential foundation movements resulted in significant structural distress in the tomb chambers and their access passages. As a result the pyramid was finished off so that the upper portions have a considerably reduced slope, giving rise to the structure being named the 'Bent Pyramid'. Abandoning the concept of buttress walls, future pyramids were built tier by tier, each tier consisting of a single layer of blocks of uniform thickness across the full width of the structure. Greater care was also taken in dressing and placing the blocks.

Kerisel (1987) describes how in Mesopotamia, over a period of three millennia, the art of building ziggurats was developed, in most cases on very weak alluvial soils. Because of the scarcity of stone these high massive structures were made of sun-baked bricks laid out in successive courses. As construction proceeded the underlying alluvium soon yielded under the weight causing the base to spread laterally. Work progressed very slowly with long pauses in between so that little by little the rate of settlement and spreading diminished. Eventually it was possible to build a small temple at the top (**Figure 3.1**). Around 2100 BC the Sumerians began to place thick layers of woven reeds between every six to eight courses of sun-dried brickwork. In this way the horizontal tensions caused by the tendency of the foundations to spread were resisted. As a result ziggurats could be built with nearly sheer sides and massive temples on top. This innovation is often cited as the earliest example of reinforced earth.

Two early examples of successful foundation engineering in China are given by Kerisel (1987). The elegant early 7th century Zhaozhou (otherwise known as Anji) Bridge (**Figures 3.2** and **3.3**) is founded on clay, which was treated by digging it out beneath the abutments and recompacting it in layers interspersed with compacted layers of broken bricks. The late 10th century 44 m high Pagoda of Longhua is founded on a thick layer of soft clay extending to a depth of about 30 m. The foundations are of brick laid on a wooden raft, which in turn rests on wooden piles driven at very close spacing – perhaps one of the earliest examples of a piled raft. The foundations remain unchanged since they were constructed over 1000 years ago.

3.2 Geotechnical engineering in the early 20th century

It is not widely appreciated what a parlous state ground engineering was in, prior to Terzaghi's contributions. Recently, as part of its centenary celebrations, the author was given the interesting task of tracing the development of foundation engineering over the last 100 years through the papers published in *The Structural Engineer* (Burland, 2008). Many of the early papers describe various techniques of foundation construction such as piles, sheet pile wall sections, coffer dams and caissons. But these papers make little reference to the mechanical properties of the ground and how its response can be assessed. For example Brooke-Bradley (1932–34) states that:

> If the bearing power of sub-soil should prove to be inadequate to carry the proposed loads, it must be artificially strengthened.

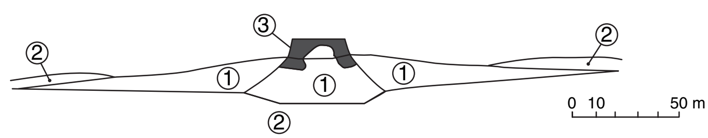

Figure 3.1 Construction of an early ziggurat. (1) Fill, (2) soft alluvium, (3) temenos – sacred enclosure
Reproduced from Kerisel (1987); Taylor & Francis Group

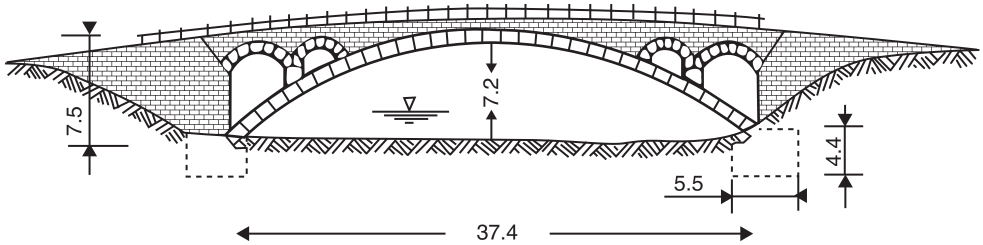

Figure 3.2 Zhaozhou Bridge – early 7th century
Reproduced from Kerisel (1987); Taylor & Francis Group

Figure 3.3 Zhaozhou Bridge

Methods of doing this are then described together with the various types of piles available for this purpose. Nowhere does one find how the 'bearing power' of the ground can be assessed in the first place. It is also stated that 'all settlement should be avoided if possible'; examples are given of damaging settlement but no guidance is given on how it could be estimated.

In the early issues of *The Structural Engineer* some space is given to the design and construction of retaining walls. In 1915 Wentworth-Shields wrote a paper on 'The stability of quay walls on earth foundations' (Wentworth-Shields, 1915). He opens with the following memorable statement:

> In spite of the large amount of experience which has been gained in the construction of quay walls, it is still one of the most difficult problems in engineering to design a wall on an earth foundation with confidence that it will be stable when completed. … Even if the designer of such a wall is assured that it will stand, he cannot with any confidence tell you what factor of safety it possesses.

In 1928 Moncrieff published a major paper in *The Structural Engineer* (Moncrieff, 1928) on earth pressure theories in relation to engineering practice. He summarises the various approaches to calculating earth pressures from Coulomb (1773) through to Bell (1915). At that time the angle of friction was generally equated with the angle of repose and Moncrieff refers to the difficulty of determining this angle for clayey soils. He cites a cutting in clay in which the side slopes varied from vertical to 1 vertical in 1½ horizontal while in places the clay was 'running down like porridge'.

It is all too clear from these early papers that, in spite of significant, even heroic, engineering achievements in the construction of major foundations, retaining structures, tunnels and dams, there was little understanding of the factors that control the mechanical behaviour of soil in terms of its strength and stiffness. Moreover, there is almost no reference to the influence of ground water on strength, stability or earth pressures. It is hardly surprising that there were frequent failures, particularly of slopes and retaining walls. This was the muddle that Terzaghi found when he first began to practise as a civil engineer.

3.3 Terzaghi, father of geotechnical engineering

Because of his work in developing the scientific and theoretical framework of soil mechanics and foundation engineering, Terzaghi is often regarded as essentially a theoretician. Nothing could be further from the truth. It is, therefore, worth reflecting on Terzaghi's struggles to develop the craft and the science of ground engineering for they have relevance in both the teaching and the practice of the discipline.

Goodman (1999) has written a most illuminating and thoroughly researched narrative of Terzaghi's life, *Engineer as Artist*. Terzaghi was born in Prague in 1883. He showed an early interest in geography, especially field exploration, and later astronomy. which evolved into a passion for mathematics. Later at school he was inspired by the natural sciences and performed brilliantly.

3.3.1 Terzaghi's education

He went on to read mechanical engineering at the Technical University of Graz. For a time he lost his way, engaging in drinking and duelling. He found the lectures were simply a set of prescriptions, which he claimed he could read for himself. Ferdinand Wittenbauer, a wise teacher, challenged Terzaghi to do better and go back to the original sources – in particular Lagrange's *Analytical Mechanics* (Lagrange, 2001).

Wittenbauer led Terzaghi gently on, guiding him not only into the excitement of scientific creativity but also in the very real social and cultural issues of the day. It was Wittenbauer who saved Terzaghi from being expelled after an over-exuberant student prank. Wittenbauer pointed out to the authorities that in the history of the university there had been only three expulsions: Tesla, who went on to revolutionise electrical technology, Riegler, who created the steam turbine, and a third who developed into a leading church architect. He went on to point out that the university was not good at choosing candidates for expulsion. Terzaghi was reprieved!

Though reading mechanical engineering, Terzaghi attended courses in geology. He was keen on climbing and it is related that he made every climbing expedition into a joyous adventure in field geology. During his compulsory year of military service he translated the *Outlines of Field-Geology* by Archibald Geikie (director of the British Geological Survey) into German. In a second edition, he actually extended it to a fuller coverage of karst features and the geomorphology of glaciated country, replacing the English examples with Austrian ones.

3.3.2 The switch to civil engineering

Terzaghi's interest in geology persuaded him that mechanical engineering was not for him. Switching to civil engineering, he returned to Graz for an extra year. He went to work for a firm specialising in hydroelectric power generation. Although his main activity was in the design of reinforced concrete, the planning of the structures was, of course, intimately involved with geology. But frequently he found the guidance of expert geologists unhelpful. He encountered many cases of failure. Significantly these were mainly due to the lack of ability to predict and control groundwater – piping failures were abundant. He also encountered many slope failures, bearing-capacity failures and structures undergoing excessive settlement.

3.3.3 Geology on its own

Recognising the difficulties that civil engineers experienced in dealing with the ground and also the obvious influence of geological factors, he concluded that it was necessary to collect as many case records as possible so as to correlate failures with geological conditions. It is well known that he then spent two intense years (1912–1914) in the western United States observing and recording. Two years that ended in disillusion and depression. The following quote from his presidential address to the 4th International Conference on Soil Mechanics and Foundation Engineering sums up his mood at that time (Terzaghi, 1957):

> At the end of the two years I took my bulky collection of data back to Europe, but when I started separating the wheat from the chaff I realised with dismay that there was practically no wheat. The net result of two years of hard labour was so disappointing that it was not even worth publishing it.

So much for geology on its own! So much for precedent and case histories on their own!

To quote Goodman (1999), the problem lay in the fact that:

> … the names geologists give to different rocks and sediments have developed mainly from a scientific curiosity about the geologic origin of these materials, whereas Terzaghi was aiming towards discerning the differences in their engineering properties.

This is still true today – the engineer needs to understand the key geotechnical properties that affect the response of the ground.

3.3.4 The birth of the science of soil mechanics

Shortly after his appointment to the Royal Ottoman Engineering University in Constantinople in 1916, Terzaghi began to search the literature for insights into the mechanical behaviour of the ground. He became increasingly frustrated. What he witnessed was a steady decline from 1880 in recorded observations and descriptions of behaviour. This was replaced by myriads of theories postulated and published without adequate supporting evidence. This experience must have been uppermost in his mind when, in his presidential address to the 1st International Conference on Soil Mechanics and Foundation Engineering, he stated the following (Terzaghi, 1936):

> In pure science a very sharp distinction is made between hypothesis, theories, and laws. The difference between these three categories resides exclusively in the weight of sustaining evidence. On the other hand, in foundation and earthwork engineering, everything is called a theory after it appears in print, and if the theory finds its way into a text book, many readers are inclined to consider it a law.

Thus, Terzaghi was emphasising the enormous importance of assembling and examining factual evidence to support empirical procedures. He also brings out the importance of instilling rigour. This is often equated with mathematics but there is at least as much rigour in observing and recording physical phenomena, developing logical argument and setting these out on paper clearly and precisely.

In 1918 Terzaghi began to carry out experiments on forces against retaining walls. He then moved on to piping phenomena and the flow beneath embankment dams. He used Forchheimer's flownet construction to analyse his observations and apply them in practice – methods that were themselves adapted from the flow of electricity. We see here the interplay between experiment and analytical modelling.

Over this period Terzaghi came to realise that geology could not become a reliable and helpful tool for engineers unless and until the mechanical behaviour of the ground could be quantified – this required systematic experimentation. On a day in March 1919, and on a single sheet of paper, he wrote down a list of experiments that would have to be performed.

Terzaghi then entered an intense period of experimental work in which he carried out oedometer (confined compression) tests and shear tests on clays and sands, thereby developing his physical understanding of the principle of effective stress (the cornerstone of soil mechanics), excess pore water pressures and the time-rate of consolidation – this was the birth of soil mechanics. To make headway with modelling the consolidation phenomenon analytically he turned to the mathematics of heat conduction. Again we see here the interplay between experiment and analytical modelling. This intense period of experimental work and theoretical modelling culminated in the publication of his seminal book *Erdbaumechanik* (Terzaghi, 1925).

3.4 The impact of soil mechanics on structural and civil engineering

In 1933, a Soil Physics Section was established at the Building Research Station (BRS) in the UK, and Dr Leonard Cooling was put in charge of it. He set up the first proper soil mechanics laboratory in Britain, equipped with the apparatus necessary to classify soils, measure their basic mechanical properties and carry out sampling. By 1935 the first investigations of civil engineering problems had begun and the group moved to the Engineering Division of BRS and was renamed the Soil Mechanics Section. It was in August 1937 that the well-known Chingford embankment dam failure occurred and the team from BRS carried out the investigation. Terzaghi was called in to redesign the embankment, and the necessary testing and analysis was carried out at BRS. This gave great impetus to the acceptance of soil mechanics as a key discipline in civil engineering in the UK.

On 6 December 1934, Terzaghi delivered a lecture before the Institution of Structural Engineers in London with the title 'The actual factor of safety in foundations' (Terzaghi, 1935). He illustrated his lecture with a large number of case histories of measured distributions of settlement across buildings and their variation with time. He was able to explain the broad features of behaviour using the basic principles of soil mechanics and foundation analysis, demonstrating how vital it is to establish the soil profile with depth and across the plan area of the building. Even so, he showed that local variations in soil properties and stratification make it impossible to predict the settlement patterns with any precision. Without actually using the term, he drew attention to the important concept of ground–structure interaction, pointing out that the structure of a building should not be treated in isolation from its foundations. He even drew attention to the fact that reinforced concrete beams can yield plastically without impairing the stability or appearance of a frame building, provided the cracking is not excessive. It is of interest to note that, in their seminal paper on the allowable settlement of buildings, Skempton and MacDonald (1956) drew extensively on the case histories provided by Terzaghi in this lecture.

Towards the end of his lecture he made the following important assertion:

> Experience alone leads to a mass of incoherent facts. But theory alone is equally worthless in the field of foundation engineering, because there are too many factors whose relative importance can be learned only from experience.

On 2 May 1939, Terzaghi delivered the 45th James Forrest Lecture at the Institution of Civil Engineers, London with the title 'Soil mechanics – a new chapter in engineering science' (Terzaghi, 1939). The lecture summarised in simple terms the basic elements of the discipline of soil mechanics and its application to a number of engineering problems ranging from earth pressure against retaining walls and the failure of earth dams due to piping through to the phenomenon of consolidation and the settlement of foundations. Early in the lecture Terzaghi made the memorable statement that:

> … in engineering practice difficulties with soils are almost exclusively due, not to the soils themselves, but to the water contained in their voids. On a planet without any water there would be no need for soil mechanics.

He was a forceful and charismatic figure and this lecture made a very profound impact on the structural and civil engineers in the UK. The late Peter Dunican, past president of the Institution of Structural Engineers, attended as a young man and told the author of how Terzaghi had electrified the audience. Many leading geotechnical engineers, including the late Sir Alec Skempton, stress what a pivotal role this lecture played in the development of soil mechanics in the UK. As with his earlier lecture to the Institution of Structural Engineers, Terzaghi emphasised very strongly the importance of retaining a balance between theory and practice in soil mechanics. He stressed most strongly that precision of prediction was not possible due to the inherent variability of the ground and construction processes.

It is clear that Terzaghi is very much more than the father of the science of soil mechanics. His contribution was to place ground engineering on a rational basis, with geology as a key supporting discipline and soil mechanics providing the scientific framework for understanding the mechanical response of the ground. He is indeed the father of geotechnical engineering, which embraces engineering geology, soil mechanics and arguably rock mechanics as well.

3.5 Conclusions

Terzaghi's development of the science and art of geotechnical engineering grew out of his experiences as a civil engineer and his gradual realisation that the underlying principles governing the mechanical properties of soil were not understood. Although his contributions are often regarded as primarily theoretical, in reality this is anything but the case. A close study of his work reveals a brilliant and passionate engineer who at all times tried to maintain a balance between underlying theoretical principles, practical experience and the handling of the uncertainties that are always present when dealing with the ground in its natural state.

It is hoped that this chapter will provide a helpful summary that puts into context Terzaghi's struggles to provide a scientific and rigorous basis for geotechnical engineering. It demonstrates his grounding in geology; the importance of gaining an understanding of the mechanical behaviour of the ground and

Figure 3.4 Karl von Terzaghi
By kind permission of the Norwegian Geotechnical Institute

groundwater by means of experiment and testing; the need to develop an analytical framework for predictive purposes and, very importantly, the key role that experience plays and the importance of case histories. Time and time again he insisted that soil mechanics is not a precise science because of the inherent variability of the ground and the uncertainty of many factors associated with construction.

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All chapters within Sections 1 *Context* and 2 *Fundamental principles* together provide a complete introduction to the Manual and no individual chapter should be read in isolation from the rest.