Historical background and evolution of Soil Mechanics

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Abstract: - The behavior of soil either as a building material or as a load receiver is particularly important and presents a paramount significance in both infrastructure and building construction. Geotechnical engineering has shown a rapid development over the last fifty years and holds a prominent position in all scientific fields of engineers. This paper mainly aims at the historical background along with the progress made on Soil Engineering as an important branch of Surveyors, Civil and Mining Engineers, where, through an important citation of technical works and constructions over time, may be considered as a significant tool for teaching and education of students.

1 Introduction

Soil Mechanics is an application of the statutory laws of engineering and hydraulics to soil material. The soil, compared to many other materials studied in engineering, such as concrete, steel, wood has two originalities. It is above all a non-continuous medium which should be studied in its entirety and in its composition, while it is also a material composed of three elements; water, air and solid granules. The materials that are involved, gravels, sand, silts and clays are totally different. The size of the particles combined with the color characterizes the type of the soil. Soil engineering and soil mechanics are both disciplines of civil engineering aiming at the study of soil with respect to its applications and behavior as a material [1].

As a science, Geotechnical engineering is dealing with mechanics of rock and soil. Mainly it focuses on the construction of foundations, retaining structures, embankments, landfills, slopes, tunnels, roadways, levees, wharves, and many other systems that contain soil or rock, or are supported by them, through proper analysis and design [2]. The main purpose in the design of geotechnical engineering is to define the shear strength and settlement of the soil through methods of analysis for the deformed soil along with the flow that the fluids follow in the structures that are either supported or made of soil, or even structures buried into the soil. It is significant for bridge and building foundations, dams, retaining walls [3, 4, 5] as well as systems of buried pipelines [6, 7]. Geotechnical engineering can be considered as not just a theoretical science, but also a science that is a product of laboratory and field tests and geotechnical exploration in general. The test results are useful to understand the behavior and properties of the soil with a view to their final incorporation into the design process. The target of this work is integrated through biographies of great researchers along with projects, constructions and scientific articles, which are accordingly presented.

2 Literature Review

The bibliographic sources [1, 2, 3, 4, 5, 6, 7] referred in introduction, were useful and helped the fundamental data to be collected. The book references [8-78] refer to selected works which cover in detail the whole range of design and construction of the soil engineering object. In fact, they are classified by category of applications in Geotechnical Engineering, starting from the most classic and usual constructions to the most special and sophisticated applications that characterize this branch of engineering science. In this way the readers of this article could obtain an important view of the latest developments in the field of soil mechanics. Bibliographic references [79-83] are the main sources for this article as they contribute to the historical background attempted by the authors with interesting information from antiquity to the Middle Ages and Renaissance and furthermore from the Coulomb period to the recent Terzaghi period of our days. Finally, the reports [84-114] refer to important research articles that have a special place in history since they date from 1776 onwards until 1960. They include research papers, experiments, instruments

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and devices, equations and solutions as well as the first conferences, concerning the evolution of soil mechanics and its applications over the last two centuries. Biographic information of distinguished authors relevant to these works can be found in the references [79-83]. Although in this article have been collected historical data from the above sources, it is nevertheless completely original, since it contains original recordings, views and judgments from the author team in its sections and subsections.

3 Scientific data

3.1 Subject-Introductory

The soil has a three-element character; solid, water and air. This complexity of its texture makes soil mechanics perhaps the most interesting branch of engineering. If the soil is used as a building material (embankments, dams, base construction in roads) it is a requisite to know both its chemical and physical properties, determined mainly by laboratory methods and field tests. If the soil is used as a load receiver (foundations, slope supports) mainly its mechanical properties and strength are necessary, along with the normal and shear stresses that develop in the ground due to the imposition of geostatic and external loads. The presence of water inside the slopes leads to an increase of the weight and simultaneously reduces the friction between the grains thus leading the slope to slip. In the case of clay soils, until the water is removed and the load is received from the solid frame of the soil mass, subsidence may occur which would cause a major problem to the bearing frame of the superstructure. For this reason, methods have been developed for rapid solidification of embankments, infrastructure projects and building foundations.

Of particular interest is also the loose soil reinforcement measures aimed at increasing the load-bearing capacity of the clay as a structural support soil.

The main object of soil mechanics is the design of soil behavior in the case of technical works construction [3, 4].

3.2 Applications

The usual applications of soil mechanics that are of particular interest, during both the design and construction period, are summarized as follows:

- The foundation of buildings in soil of moderate or poor quality. [8, 9, 10, 11]
- On-site tests, along with similar tests in the laboratory to define the physical and mechanical characteristics of the soil [12, 13]
- The stability of slopes against static and dynamic loads [14, 15, 16, 17, 18, 19]

- The construction of slopes with a calculation of tolerable displacements in the case of a seismic excitation [20, 21, 22, 23, 24, 25, 26]
- The construction of geotechnical works using finite elements and possibility-based methods [27, 28, 29, 30, 31, 32, 33, and 34]
- Supports of the ground sides with retaining walls or other support systems [35, 36, 37, 38, 39, 40]
- The construction of underground works (tunnels, pipelines, underground tanks) [41, 42, 43]
- The use of soil as a material for the construction of embankments and earthen dams [44, 45, 46, 47, and 48]
- Landslides of technical works and improvement of loose soils [41, 49, 50, 51, 52, 53]
- The construction of roads along with their stabilization [54, 55, 56, 57, 58, 59]
- The construction of external port projects along with coast protection works [41, 60, 61, and 62]
- Slope coating on river banks for protection against erosion as well as bottom stabilization projects [63, 64, 65, 66, 67, 68, 69]
- The degradation of groundwater level, problems related to the environmental protection and the groundwater flows [41, 70, 71, 72, 73, 74 and 75]
- The foundation and construction of floating platforms for the extraction of oil and mineral wealth [76, 77, 78]

All the above applications must be carried out in accordance with the existing regulations based always on safety, but considering the economy of materials, despite the conflict between the two concepts (safety – economy).

3.3 Historical data

The history of soil mechanics is particularly interesting and should be studied properly. The opposition between the scientific communities regarding the first appearance of works related to soil mechanics is worth mentioning. According to most researchers, this science begins in the 18th century. However, in the opinion of the authors, it would be unfair not to make even a single reference to the period of antiquity, where important constructions have been recorded.

More specifically: In the ancient Egypt, where a great civilization developed along the Nile River, wonderful works have been constructed, such as pyramids and dams, through steep piles of stones, sliding restraint and caissons. In particular, the building of the pyramids faced many and tremendous challenges regarding stability of slopes, foundations, and building of underground chambers [DAS 79]. In Mesopotamia were found monuments that presented

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large settlements which were treated with reinforcement with woven reed mats, such as the Ziggurat at Aqar Quf built in the 14th century near the banks of the Euphrates River. In ancient Greece strip foundations for concentrated loads were used for the construction of the Parthenon, while in Delos iron clamps were connecting the foundation blocks (Figs. 1, 2, 3, 4, 5).
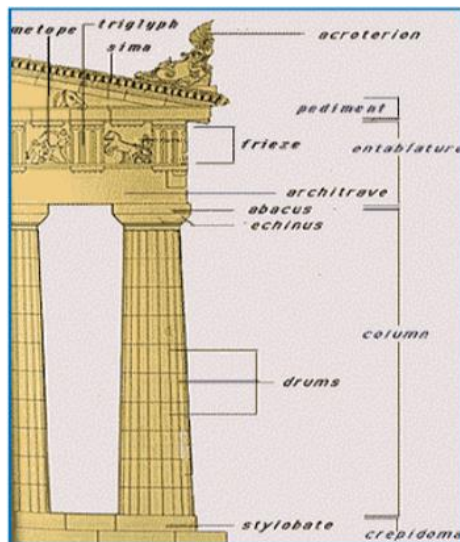

Fig.1 Parthenon in Athens

Fig.2 Doric order

Also retaining walls were used in the temple of Demeter in Pergamum as shown in Fig. 6 [80].

In ancient Rome arches behind retaining walls, roads, concrete foundations and cofferdams appear for the first time, while texts are preserved, from which it seems that the problems of the foundations were discussed with great care and also some preliminary research was carried out. Vitruvius (1st century BC) in the work "Architecture" gives information about the loading capacity of soil and piles, along with a technique of improving the foundation soil [41]. At the same time, he drafted the so-called Vitruvius - Code of Practice, depending on the type of project to be constructed. Actually, he presented the technology of that period in a ten-volume account [80].
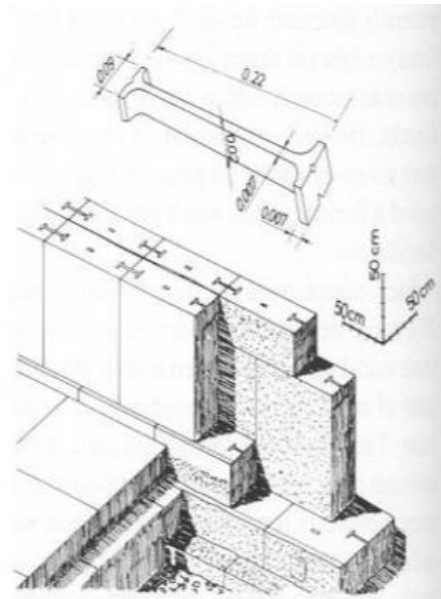

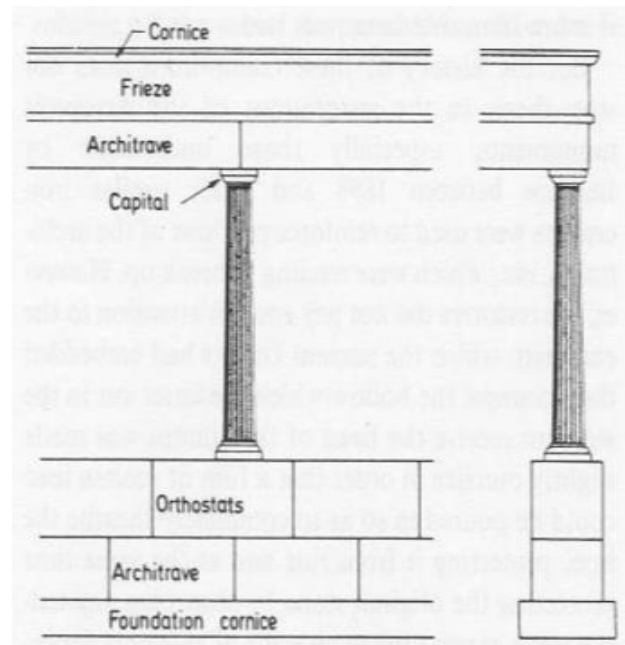Fig.3 Foundations at Delos (400 B.C)

Fig.4 Underground columns of Doric order: load concentration orthostats: long blocks of dressed stone (column foundation wall) wider foundation base.
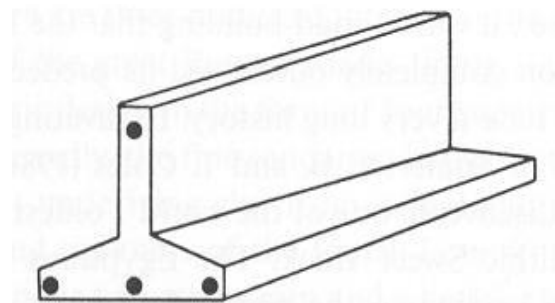

Fig.5 Present adaptation

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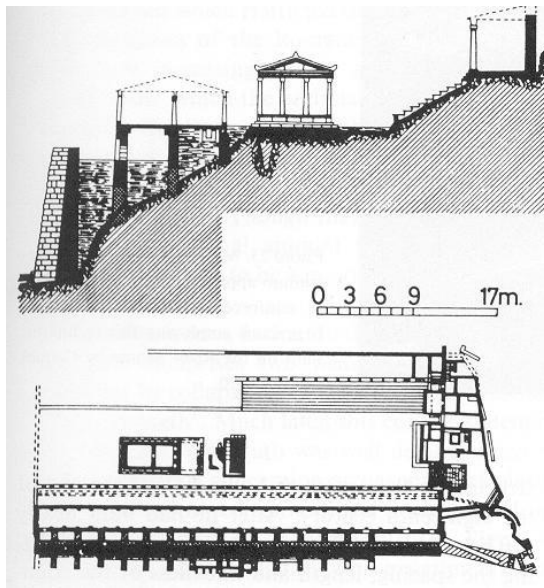Emmanouil Papadimitriou, Evangelos Paschalis

Fig. 6 The Temple of Demeter in Pergamum (2nd century BC): Retaining wall for its terrace [80]

It has been observed that constructions founded by fired earth slabs with wooden reinforcement (Fig. 7) had been eroded after flooding, which, eventually, led to a collapse of many buildings.
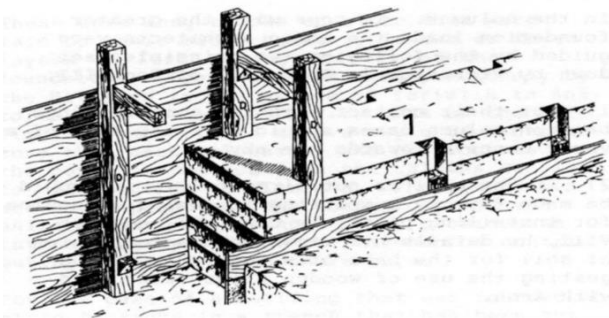

Fig. 7 Example: Roman Shallow Foundations [80]

Finally, in ancient China, techniques for soil compaction (Fig. 8) were developed for the first time according to the Sung code (1103) along with surface (i.e. shallow) bridge foundations [80].
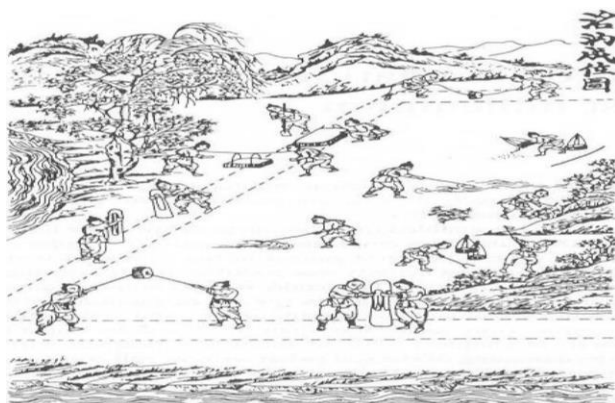

Fig. 8 Old China — compaction techniques [80]

The main problems that constructions of the medieval years were facing concerned the loading capacity of the soil and the non-uniform settlement of foundation on a soft soil. The most characteristic case is the Leaning bell tower, of the cathedral of the city of Pisa in Italy, the famous Leaning Tower of Pisa [1, 80].

Fig. 9 The Leaning Tower of Pisa [79]

The building of the Tower started in 1173 and lasted longer than 200 years. Due to its great weight -about 14,700 tons- the tower is supported on a 20 m diameter circular foundation. However, the unstable soil due to a weak clay layer at about 11 m depth was the reason to make the tower to tilt in the past, thus giving to it its worldwide main characteristic (Figs.9, 10).

Actually, the soft ground combined with a huge load of the foundation, led to a situation close to the limit equilibrium [80].

With a height of 55 m, the tower became more than 5 m out of plumb. A fear of collapse or falling over kept the tower closed in 1900. Recently the soil under the crucial parts of the foundations has been properly excavated and removed, resulting in a stabilization of the whole structure and simultaneously reducing the tilt, which, although less noticeable, of course, still exists for historical and touristic reasons.

Long in the past, similar situations in the behavior of soil during construction, led scientists and engineers who encountered various foundation problems to start to address both the behavior and properties of the soil in a more methodical way.

A new scientific period was therefore established, beginning in the first part of the 18th century [79].

During the Renaissance, by the rise of letters and arts but especially mathematics and physics, empirical methods began to be replaced by computer-based techniques.

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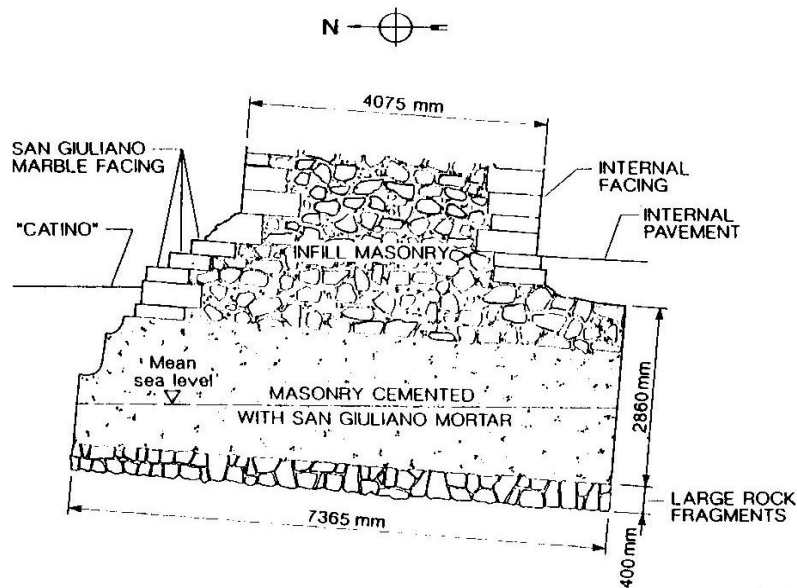Emmanouil Papadimitriou, Evangelos Paschalis
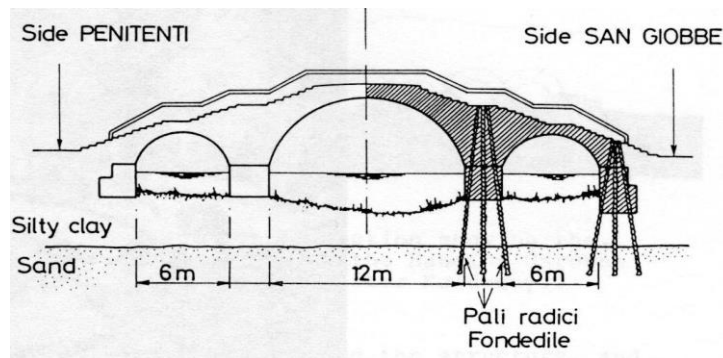
Fig. 10 Annular shallow foundation

Fig. 11 The bridge "Tre Archi" in Venice, 1688 [80]

A typical example is that of the bridges in Venice (Fig. 11). In this construction the foundation technique is depicted, where:

- Into the masonry there were drilled Root piles
- Inside small cofferdams, at a small depth, were founded Abutments.
- Inside wooden caissons, directly on the river bed, there were built Piers.

Leaving aside antiquity, the middle Ages and the Renaissance, during 18th to 20th century there was a great development in the science of soil mechanics. In that period, the professor of Imperial College A. Skempton distinguished four sub-periods as a result to the experimental works and publications of K. Terzaghi, who was and still is considered to be the founder of modern soil mechanics. The four sub-periods are:

- **Pre-classical**, from 1700 to 1774 A.D
- **Classical**:
  - phase-1 inaugurated by Coulomb in 1774, up to1856

- phase-2 starting with the Darcy's work related to the water flow passing through the soil and the permeability in 1856, up to 1910
- **Modern Soil Mechanics phase-1**: starting from the works of the Swedish scientist A. Atterberg in 1910, up to 1927
- **Modern Soil Mechanics phase-2**: where the publication of work's results from the founder of modern soil science K. Terzaghi came up from 1927, up to present [79], [80].

However, each of these periods was marked by significant experimental work that was preceded or accompanied by the development of theories that were the necessary tools for engineers in the design and construction of their works. It is therefore scientifically logic to collect measurements and observations, without which progress could not be made. [81]

The first, **pre-classical period,** was characterized from the studies, which were mainly concentrated on the natural slope of earth and the unit weights for the

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different kinds of soil, along with semiempirical theories referred to the pressure of earth.

Henri Gautier (1660–1737) a French royal engineer, investigated in 1717, the physical slopes of the soil just before overturning of a pile. As a result he formulated the design procedure of a retaining wall. The term *angle of repose* is today related with the *natural slope*.

Following the above investigation, the *ordinary earth* and the *clean dry sand* had a natural slope of 45 and 31 degrees respectively. Furthermore, the unit weight of the above materials was suggested to be respectively 13.4 and 18.1 kN/m^3. There were not announced any test results on clay.

Bernard Forest de Belidor (1671–1761), in 1729 extended the theory which was presented in 1717 by **Gautier** for the lateral earth pressure appearing on retaining walls, publishing in France a textbook for civil engineers and military. In his textbook, de Belidor classified soil for foundation problems as:

Classification	Unit weight (kN/m³)
Rock	--
Firm or hard sand; compressible sand	16.7 − 18.4
Ordinary earth (dry locations)	13.4
Soft earth (primarily silt)	16.0
Clay	18.9

Jean Rodolphe Perronet (1708–1794), a French engineer who investigated the stability of slopes, offered in this period an additional significant contribution around 1769, distinguishing it between intact ground and fills [79].

During the **phase-1 of Classical period**, the progress in the area of soil mechanics appeared mainly from scientists and engineers in France. The most famous came from **Charles Augustin Coulomb** (1736–1806), known from his famous law, where he describes the electrostatic force of attraction and repulsion. He presented his famous paper in 1776 at the French Academy of Sciences, where, he used the principles to calculate the extreme values between which the real place of the sliding area behind a retaining wall could be determined. In this procedure, Coulomb utilized the laws holding for cohesion and friction of solids. It should be noted that the concept of friction in that period was already known and Coulomb induced only the cohesion term.

Although he did not express the equation for shear strength in the form we use it, i.e. $\tau = c + \sigma \cdot \tan\varphi$, he applied it in a similar way. Actually, this is one of the earliest published theories in soil mechanics, where the concepts of active and passive pressure are presented [84]. Coulomb is considered as a pioneer in the area of geotechnical engineering for his contribution in the analysis of retaining walls.
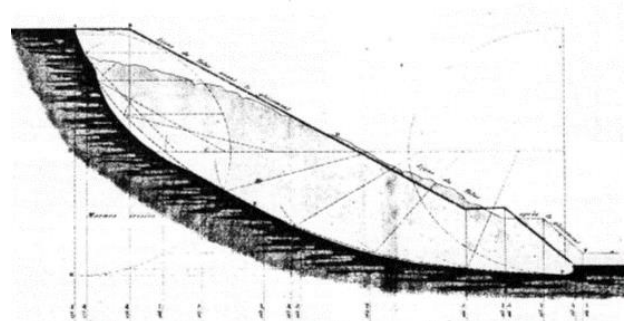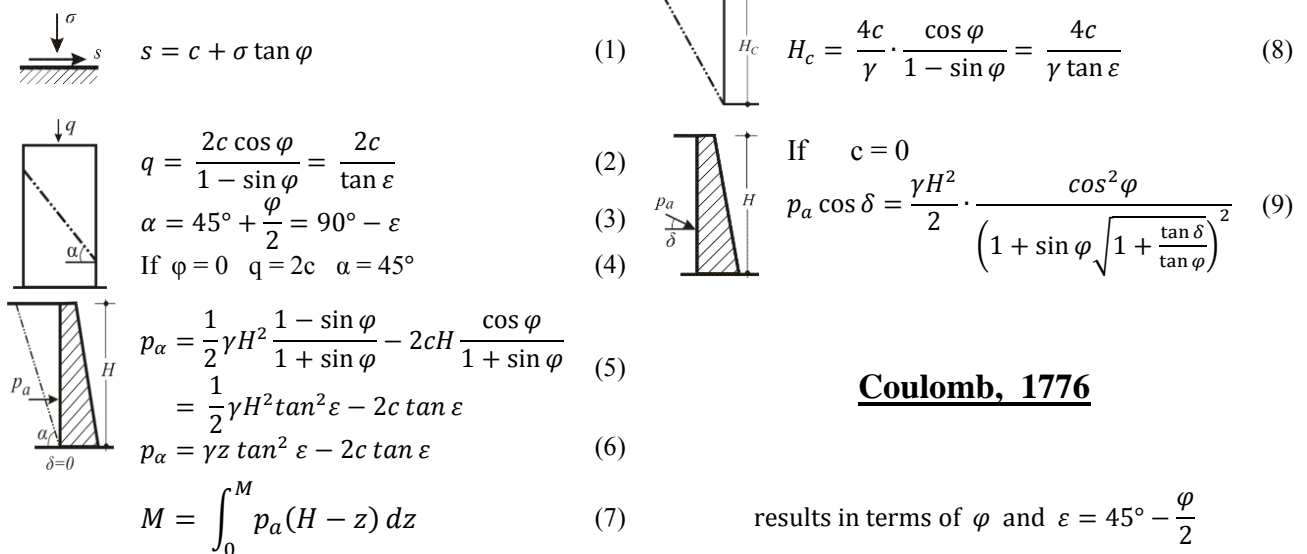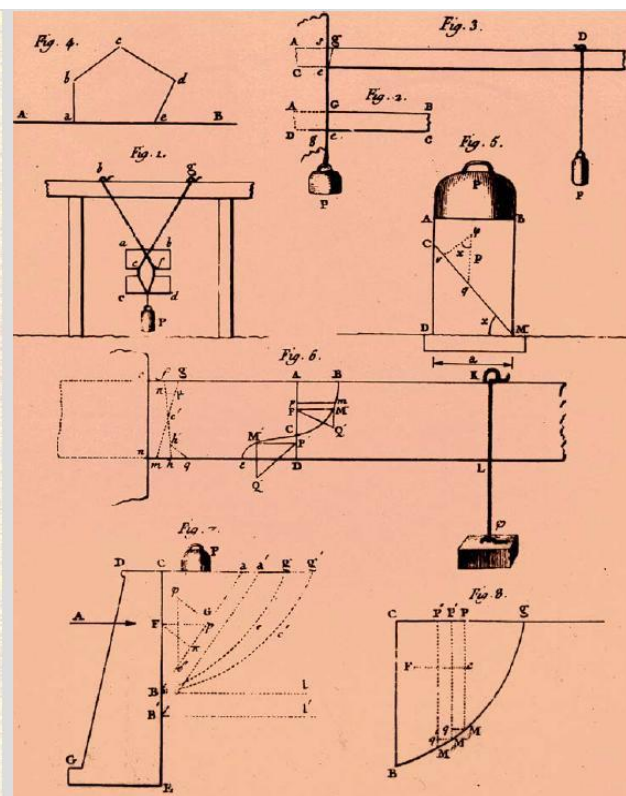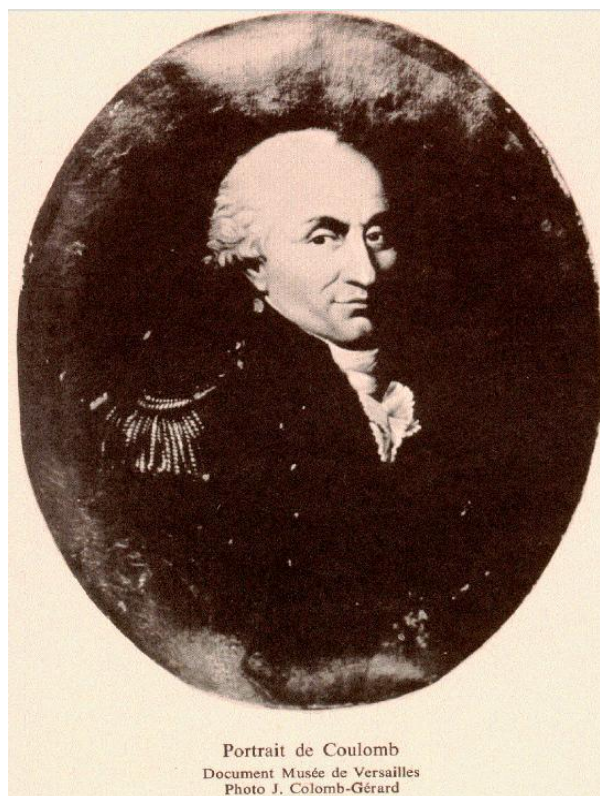

Portrait de Coulomb
Document Musée de Versailles
Photo J. Colomb-Gérard

Fig. 12 Portrait and calculations of Charles Augustin Coulomb [80].

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$$s = c + \sigma \tan \varphi \qquad (1)$$

$$q = \frac{2c \cos \varphi}{1 - \sin \varphi} = \frac{2c}{\tan \varepsilon} \qquad (2)$$

$$\alpha = 45° + \frac{\varphi}{2} = 90° - \varepsilon \qquad (3)$$

$$\text{If } \varphi = 0 \quad q = 2c \quad \alpha = 45° \qquad (4)$$

$$p_\alpha = \frac{1}{2}\gamma H^2 \frac{1 - \sin \varphi}{1 + \sin \varphi} - 2cH \frac{\cos \varphi}{1 + \sin \varphi} \qquad (5)$$

$$= \frac{1}{2}\gamma H^2 tan^2 \varepsilon - 2c \tan \varepsilon$$

$$p_\alpha = \gamma z \tan^2 \varepsilon - 2c \tan \varepsilon \qquad (6)$$

$$M = \int_0^M p_a (H - z)\, dz \qquad (7)$$

$$H_c = \frac{4c}{\gamma} \cdot \frac{\cos \varphi}{1 - \sin \varphi} = \frac{4c}{\gamma \tan \varepsilon} \qquad (8)$$

$$\text{If} \quad c = 0$$

$$p_a \cos \delta = \frac{\gamma H^2}{2} \cdot \frac{cos^2 \varphi}{\left(1 + \sin \varphi \sqrt{1 + \frac{\tan \delta}{\tan \varphi}}\right)^2} \qquad (9)$$

Coulomb, 1776

results in terms of φ and $\varepsilon = 45° - \dfrac{\varphi}{2}$

Fig. 13 Equations and sketches from Coulomb's contribution to the science of soil engineering (French Academy of Sciences) [80].

His name is one of the 72 names mentioned in the list of the Eiffel Tower [1, 79 and 80].

The Coulomb's theory was accepted later, in 1790, by **Gaspard Clair Marie Riche de Prony** (1755–1839), a distinguished French civil engineer, Chair of Mechanics at the famous Ecole Polytechnique. He presented his work in his leading textbook, *Nouvelle Architecture Hydraulique* (Vol. 1, Paris, 1790) [85]. In 1820, an extended Coulomb's theory on the active earth pressure of a cohesive fill and also short-term stability of excavated clay slopes, appeared by the French scientists:

- Engineer **Jacques Frederic Francais** (1775–1833) [86] and
- Professor of Applied Mechanics **Claude Louis Marie Henri Navier** (1785–1836) [87],

both "anciens élèves de l' École Polytechnique".

The above cases were relevant to both the supporting surcharge and inclined backfills.

Jean Victor Poncelet (1788–1867), who was a military Engineer and Professor of Mechanics at the University of Sorbonne, extended in 1840 Coulomb's theory. He determined graphically the magnitude of lateral earth pressure that appears on both vertical and inclined retaining walls with arbitrarily broken polygonal ground surfaces [88]. For shallow foundations, he provided the theory of the first ultimate bearing-capacity. He was also distinguished for his work in the Applied Mechanics and Hydraulics.

Alexandre Collin (1808–1890), an engineer who studied at the Ecole Polytechnique, introduced in 1846 details for deep slips (Fig. 14) in slopes of clay,

cuttings, and embankments. He considered that in each case the failure appears when the mobilized cohesion of the soils is greater than the existing one. He determined profiles of slip surfaces in clay slopes and approximated the actual failure surfaces by arcs of cycloids. Furthermore, he wrote his works on many engineering subjects including hydrology and grouting [89].

Fig. 14 Slope stability analysis by Colin, 1846. [80]

Generally, the Phase 1 of the classical period of soil mechanics ends in 1857, when **William John Macquorn Rankine** (1820–1872), who was a Professor of the Civil Engineering Department at the Glasgow University, published his first work. This work, presenting the pressures on earth and also the stability of retaining walls, was a great advance in soil mechanics [90], while his teaching and writings exerted a strong influence on British engineering education and practice. His theory was actually based on the corresponding of Coulomb, however in a simple way.

About a hundred years after Coulomb, the German scientist **Otto Mohr** improved Coulomb's theory of

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impulses and developed the necessary techniques for depicting graphically a two-dimensional stress-strain situation, through the famous Mohr's circle.

The two theories, Coulomb's and Mohr's in a plane stress-strain situation, combined later to develop the well-known theory of Mohr-Coulomb [79, 80].

During **Classical Soil Mechanics Period Phase - 2** (1856–1910) a number of laboratory tests on sand were realized, the results of which appeared in the literature. Among these, a significant publication was that of **Henri Philibert Gaspard Darcy** (1803-1858) who was a French engineer. Rose to a senior position at the Ponts et Chaussées, working on water supply at Dijon, on the Paris-Lyon railway, and in Paris, he presented in 1856 [91], a research on the sand filters permeability. These tests led Darcy to define the well-known up to date term of hydraulic conductivity for soil, *coefficient of permeability k,* which is a very useful parameter in geotechnical engineering. In his tests, Darcy used a medium grain size sand with a porosity of 38%. The value of k was about 0.03 cm/s. Laboratory tests were also conducted by the Prof. of Astronomy **Sir George Howard Darwin** (1845-1912), aiming at defining the necessary moment to overturn a hinged wall retaining sand in a loose and dense compact environment [92].

Joseph Valentin Boussinesq (1842–1929), Physicist and Mathematician, published in 1885 another significant work, where he developed a theory about the way that the stresses are distributed in areas under loading in a medium homogeneous, isotropic, elastic and semi-infinite. He also calculated both the stresses and displacements of the elastic field. His celebrated *Application des potentiels*, providing stresses and displacements in elastic foundations, was published in 1885 [93].

In 1887, **Osborne Reynolds** (1842–1912), fellow of the Royal Society and Professor of Engineering at Manchester from 1868 to 1905, was distinguished for his research in hydraulics. He presented the dilatancy phenomenon in sand [94].

Significant investigations in this period were also made by **John Clibborn** (1847–1938) and **John Stuart Beresford** (1845–1925), regarding the flow of water through sand bed and uplift pressure [79, 80].

The **Modern Soil Mechanics period** (1910–1927) is characterized by the publication of a large number of research results conducted on clays, were properties and fundamental parameters of clay were defined. A list of the most significant publications follows:

Albert Mauritz Atterberg (1846–1916), who was a Swedish soil scientist and chemist, researcher at the Agricultural Institute of Sweden, defined, around in 1908, the clay-size fractions as a by weight percentage of particles, the size of which is less than 2 microns. He understood the significant role that clay particles play in the soil. In 1911, he justified the cohesion of cohesive soils, depending on the water level of the clay, and defined the limits of shrinkage, plastic and liquid [95]. He further defined the index of plasticity as the difference between the limits of plastic and liquid (Atterberg, 1911). In October 1909, the failure of an earth dam, height of 17 m, built in France at Charmes between 1902 and 1906, was the reason to start in 1914 an investigation by the French engineer **Jean Frontard** (1884–1962). He actually run undrained double-shear tests, under normal load ($\sigma \neq 0$) on 200 mm thick and 0.77 m^2 clay specimens under vertical constant stress, aiming at defining the parameters of shear strength. The tests, performed under different vertical loads, allowing him to determine the angle of internal friction [96].

Arthur Langley Bell (1874–1956), an English Civil engineer, investigated the design and construction of the outer seawall at Rosyth Dockyard. As a result, he related the lateral pressure and resistance in clay with the bearing capacity of shallow foundations in clay [97]. He was also the first engineer who used a direct shear-box test in order to define the undrained shear strength of undisturbed specimens of clay. His work marks the beginning of modern Soil Engineering.

J. Résal (1854-1919), a distinguished Engineer for bridge designs, in the second volume of his research on ground thrusts (1910), examined clay soils, based on his observations on the tensile strength of clays [98].

Wolmar Fellenius (1876–1957), from his post as a Professor of Hydraulics at the Stockholm Royal Institute of Technology (KTH), was investigating the stability of dams, quays and slopes. Being honored in his PhD from the universities of Karlsruhe and Darmstadt Germany, he established the stability analysis of saturated clay slopes (where $\varphi=0$) under the term that the critical surface of sliding is a segment of a sphere. He extended the two-dimensional method of slip circle to both cohesive soils and soils with friction and cohesion. He further presented for foundations the concept of the safety factor, in the form that it is used today (Fellenius 1926a, 1926b) [99, 100]. This factor is expressed by the ratio of the total available strength and the forces that act, while, for the slope stability, the factor accordingly expresses the ratio of the resisting and forcing rotating moments. The above results were verified in his papers, which were published in 1918 and 1926. The later of the two papers provided exact numerical answers solving the stability of spherical slip surfaces that pass through the slope's toe.

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Karl Terzaghi (1883–1963), according to ASCE was an Austrian Geologist and Civil Engineer who devoted a large part of his scientific life to develop the theory of clay consolidation in its present form. His passion for Geology along with significant experience acquired through projects in Russia and Croatia inspired him to look into the conditions of underlying construction projects along with their engineering consequences. This research covered the period 1919 to 1924.
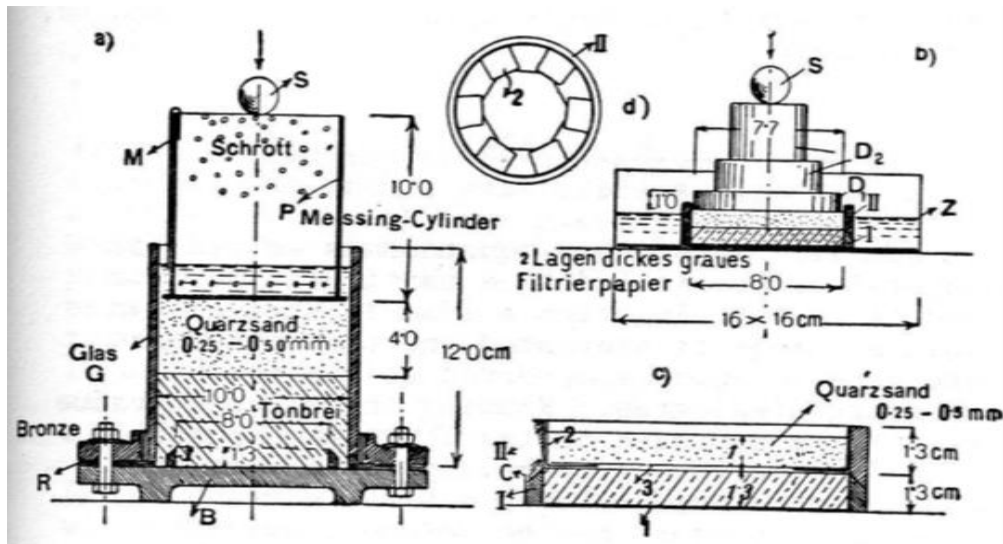
Fig.15 a) Terzaghi – Compressibility test [80]

Five different specimens of clay soils were used.
The consolidation theory, based on the Physics of Soils, was published in Vienna, in 1925 [101], under the title *Erdbaumechanik* (translated: Earthwork of Mechanics), and was Terzaghi's celebrated book. Among others it was presented in it the fundamental differential equation necessary to start the procedure of consolidation, which is related to the level of clay's compression. This equation is similar to that of heat's diffusion in solids. In that book was also incorporated the theory of effective stresses to justify the way in which the soil behaves under load. The book was successful and led to positisions at MIT and Technical University of Vienna (ASCE).

b) Karl von Terzaghi (1883−1963) [79]

Terzaghi was continuously working for his ideas to be accepted by the scientists, while, simultaneously, he was also occupying as consulting engineer for many construction projects.
Accepting a position of Professor at the Technical University of Vienna in October 1929, he returned in Europe. He was shortly recognized by the circle of civil engineers involved in soil mechanics.
Harvard University offered him a professorship in 1939, which he obviously accepted, thus continuing his carrier in the USA. Between 1939 to 1960 his authorship consists of two books [102], [103] and over 100 papers, covering the area of soil failure, vibration problems and soil mechanics. Terzaghi was also involved as a consultant for the construction of earth dams, landslides' stabilization, buildings' foundations, waterfronts, highways, and airports [104. He is the only engineer so far, who was 4 times honored with the highest award, the Norman medal, of the American Society of Civil Engineers (ASCE) [79, 80, 81, 82, 104].
Modern Soil Mechanics phase-2 (after 1927).
From all the above it is obvious that Karl Terzaghi had a general recognition worldwide. This is the reason that he is considered as the father of Modern Soil Mechanics and Geotechnical Engineering. His published theory in the book '*Erdbaumechanik auf Bodenphysikalisher Grundlage*' was, in 1925, the starting point of a new period in soil mechanics. Karl Terzaghi was in 1936 Head of the International Society of Soil Mechanics

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and Foundation Engineering (ISSMFE) conference, which was first held at Harvard University.

Prof **Arthur Casagrande** of Harvard University, was the main organizer of the conference, which was realized due to his significant efforts during his career to the fields of Engineering Geology and Geotechnical Engineering. He was the inventor of an ingenious worldwide soil testing apparatus, [105] along with a fundamental research on seepage and liquefaction. Casagrande was also the creator and pioneer of a teaching program in Soil Mechanics at Harvard University in the 1930s.

The conference was international and attended by about 200 individuals, representing 21 countries. It should be noted that it was inspired and guided by Terzaghi.

The presented papers covered a wide scientific area of topics, like:

- Arching theory of earth pressure
- Centrifuge testing
- Consolidation
- Earthquake and soil liquefaction
- Effective stress
- Elastic theory and stress distribution
- Frost action
- Machine vibration
- Preloading for settlement control
- Shear strength
- Swelling clays
- Testing with Dutch cone penetrometer

Nearly every sector of soil mechanics along with geotechnical engineering around the world has been benefited by Terzaghi.

In 1985, **Ralph Peck** [106] acknowledged Terzaghi's contribution. The ISSMFE conference was in 1936 only a starting point followed by a number of publications in the soil mechanics and geotechnical engineering, as:

- *Theoretical Soil Mechanics* by Karl Terzaghi in 1943, Wiley, New York [103].
- *Soil Mechanics in Engineering Practice* by Karl Terzaghi and Ralph Peck in 1948, Wiley, New York) [107]. It was considered a best seller, translated in 17 languages, including Russian and Chinese.
- *Fundamentals of Soil Mechanics* by Donald W. Taylor in 1948 (Wiley, New York) [108].
- *Geotechnique,* the international journal of soil mechanics, first appeared in 1948 in England.

It must be noticed that **Ralph Peck** was from1938 to 1939, a student of Arthur Casagrande, taking courses from him in a new subject called "soil mechanics". When later he became a professor at Illinois Institute

of Technology in Chicago, he began a series of famous presentations and articles published in the journal of ASCE Transactions. As a result, the committee of ASCE's prestigious Norman Medal acknowledged in 1944 the research papers of Peck related to the braced excavations, by simulating them to equivalent pressure diagrams. Due to the poor research in the area of foundation engineering, Peck, in 1949, based his teaching at the University of Illinois on the tension cracks, which appeared in a step foundation in Lowndes, 1928, as shown in Fig. 16.
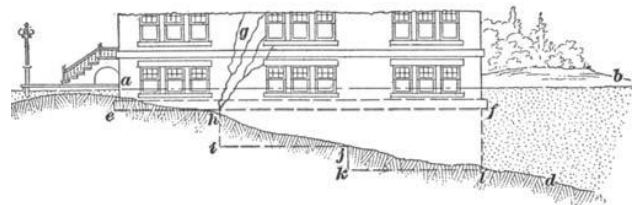

Fig. 16 Tension cracks emanating from a stepped foundation. [83]

It would be an omission not to mention that **Peck**, **Thornburn** and **Hanson** (Fig. 17), were the three instructors from the University of Illinois who coauthored the "Foundation Engineering", first published in 1953. A revised edition was released in 1974 [109].

In the period between 1948 and 1960 two other significant publications were:

Fig. 17 From left: Ralph B. Peck, Thomas H. Thornburn, and Walter E. Hanson [83]

1. **A.W. Skempton's** paper on *A* and *B* pore pressure parameters [110], basically aiming at the practicality of calculating the effective stress for engineering works, and
2. *"The Measurement of Soil Properties in the Triaxial Text"* by **A. W. Bishop and B. J. Henkel** (Arnold, London) in 1957 [111].

Sir **Alec Westley Skempton,** Professor at Imperial College was full of honors and active until the end of his life, on 9 August 2001. He was scientifically

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notorious in his active time and is considered a pioneer of soil mechanics.

In the research field, a distinguished British academic and geotechnical engineer was **A. W. Bishop.** He worked at *Imperial College* London and was famous for the Bishop's Simplified Procedure in stability of slopes.

B. J. Henkel was in Alec Skempton's group at Imperial College London, from 1949. He became a professor and head of the Geotechnical Engineering Department at Columbia University. Among others, he examined underwater landslides in the Gulf of Mexico, organized a conference on earth pressure, analyzed soil stress conditions and the stability of deep excavations in clay soils.

Laurits Bjerrum, son of a Danish surgeon, was a civil engineering, graduated from the Technical University of Denmark, in 1941. He was particularly known for his work on the shear resistance of clays. In doing so, he built on the work of **Mikael Juul Hvorslev** and, like Alan W. Bishop in England, at the same time, he developed the measurements of triaxial device [112]. The soft marine clays that often lead to landslides in Norway was a special issue of his research. He gave both the Terzaghi Lecture of the ASCE (1967) and the Rankine Lecture (1967) of the Institution of Civil Engineers (ICE). In 1971 he received the Terzaghi Award from ASCE and became later member of the Danish and Norwegian national civil engineering societies and national engineering academies, the Norwegian Academy of Sciences, the ASCE (1972) and the ICE. From 1951 until his death, he kept the post of director in the Geotechnical Institute of Norway (NGI), founded this period in Oslo, which he finally developed into a leading research institute in Europe.

In the post-war period, the contribution of **Kenneth 'Ken' Harry Roscoe** (1914–1970) has also been proven important to the science of Soil Mechanics. Roscoe was a distinguished British civil engineer who considerably contributed to develop the theory of plasticity in soil mechanics. A research on the yielding point of soil in 1958, based on some data of the Cambridge simple shear test apparatus along with much more extensive data of triaxial tests conducted by Prof. Skempton in the Laboratories of Imperial College, resulted in the development of the critical state theory of soil mechanics (**Roscoe**, **Schofield** & **Wroth** 1958) [113], which actually was a pioneering work to what is until today acknowledged as the *Cam clay constitutive model* for the soil behavior.

It is however worth mentioning that solutions applied to a number of geotechnical problems through the finite elements and finite differences computer aided programs have been proven a significant tool, already since 1950s. This might be a reason that the science of geotechnical engineering is today considered as a mature branch of civil engineering, attracting many engineers to obtain this specialization.

Bishop, Alpan, Blight, and **Donald** provided in 1960, a number of experimental results along with guidelines for the various parameters that control the strength of cohesive soils when they are partially saturated [114]. A significant progress has been made ever since on the behavior of unsaturated soils in correlation to their compressibility, strength and not only, affecting the construction.

Accomplishing its true scientific scope, the ISSMFE has already transformed to ISSMGE (International Society of Soil Mechanics and Geotechnical Engineering) in 1997. Its technical committees organize and sometimes support financially various conferences, including all the subjects mentioned in section 3.2. [79, 80, 81, 82, ASCE].

4. Greek projects

At the National Technical University of Athens (NTUA), foundation courses were taught from the interwar period, after which soil engineering were added. In 1982 the sector of Geotechnics was created at the School of Civil Engineering, in 2004 the direction of geotechnical engineering was established, while, since 1998, the postgraduate course in Design and Construction of Underground Works has been established (together with the School of Mining). Geotechnical engineering, the newest sector of civil engineering, is directed for the design and construction of infrastructure projects combining safety and economy. Main concerns of geotechnical engineering are the following:

- safe foundation of bridges, the stability of slopes and the support of tunnels,
- safety support of excavations and buildings,
- proper sizing combined with the use of appropriate materials in dams and embankments,
- proper paving of airport roads,
- the resistance of piers, arms and breakwaters against the energy of waves,
- correct construction of landfills along with their harmonious integration into the environment,
- prediction of the earthquake transmission and the interaction of soil-structures,
- improving soil mass and preventing liquefaction,
- correct dimensioning of both piles and retaining walls and

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- many other geotechnical works.

Below is a brief report of infrastructure projects in the Greek territory presented in his book by the distinguished Dr. Civil and Geotechnical Engineer Spyros Kavounidis [41]. In more detail:

In the Eupaline Aqueduct of Samos, built in the 6th century BC, an access tunnel was simultaneously opened from both fronts, while, at the same time, a deep ditch was opened at the bottom, where the clay water pipes were placed. Since 1992, this project, being incorporated in the List of UNESCO's World Heritage, was declared in 2015 as the International Landmark of Tunneling by the International Association of Tunnels and Underground Works.

On the old bridge of Arta, fixing works of the pedestals were carried out as well as on the slopes of the Holy Monastery of Stavronikita on Mount Athos. The geotechnical work of the Corinth canal was completed by the new road bridge, which, due to the high level of seismicity in the area, was placed on a pedestal with seismic insulation along with shaft supports.

Quite recently, the Kallidromo tunnel of the new railway line Tithorea-Lianokladi, the railway tunnel of Tempi in the Athens-Thessaloniki network, the Dichalorema tunnel of the Athens-Lamia Motorway, the Athens and Thessaloniki metro, were also built.

In all the above projects, the most modern methods of geotechnical engineering related to the opening of tunnels were used. Also the dam of Mornos in Fokida, the dam of Evinos in Orini Nafpaktia as well as the stone-built dam of Thesavros of Nestos which, despite the geological problems that existed, finally became possible to build them. To achieve this, a variety of geotechnical interventions were carried out, such as landslide restoration, sealing of clay cores, anchorages and drains.

A significant achievement is also the foundation of the Rio Antirrio bridge, which, of course, should not be overlooked due to various and crucial problems that arose, such as the:

a) great depth of the sea (approximately 65 m)
b) loose / soft and thick foundation soil and
c) strong seismic coefficient ($maxS_A = 1.2$ g).

To strengthen the soil mass, the soil was "nailed up" with huge steel pipes on which a 3m layer of large shingles was built to accommodate the foundation, which was achieved with the foundation-pedestal-pillar system.

Also important projects with many geotechnical applications are the bridge of the Serbs on the river Aliakmonas, the cable – stayed new bridge of Chalkida on the strait of Evripos and the twin Votonosi viaduct of the Egnatia Aviation, which was founded through wells of reinforced concrete.

The Soil Mechanics contribution is also important in the construction of the new ports of Igoumenitsa and Patras due to the geotechnically difficult materials of the seabed. The following geotechnical works were carried out in these ports:

a) Implantation of geosynthetic drains at depths of 15-20 m in order to accelerate solidification and increase the shear strength.
b) Preloading of the quay area with a gradually constructed embankment, in order to improve the shear characteristics of the soft clay slurry layer, before the completion of the quay walls construction.
c) Construction of gravel piles aiming at strengthening the resistance of the upper part of the soft clay layer and further compact the foundation soil.
d) Removal of the preload embankment, installation of the caissons, filling of rear cells with gravel material and completion of the construction.

Of great importance is the project of the submarine tunnel Preveza - Akti 910 m long, that bridges the sea strait which separates the Central Greece from Epirus at the opening of the Amvrakikos gulf. For a safe load bearing and seismic behavior, the seabed soil was improved for the whole length of the tunnel through the use of gravel piles to prevent soil liquefaction.

In the field of aviation and in order to expand the runway 10/28 of the airport of Thessaloniki (Macedonia), an embankment of granular materials was built in the sea on a very soft bottom with systematic measurements of surface and internal sedimentations so that the attenuation of the solidification rate can be determined. Due to damage and loading, the existing roads of different regional airports in the country, were upgraded through appropriate geotechnical design of the required restoration projects.

A special place in the construction of highway embankments is occupied by the PATHE Embankment of Lightweight Materials (EPS). This is the first and largest application of light embankments made of expanded polystyrene in Greece and one of the largest internationally, with a total length of 1,030 m and a height of up to 8.5 m. On the Ionian Aviation highway, in the section of the Amfilochia bypass, a reinforced embankment of a maximum height of 21 m was constructed, the facade of which was formed by the technique of wrapping (wrap-around facing) the geosynthetic reinforcements placed in predetermined locations.

The construction of a Landfill, which is one of the basic elements of an environmental infrastructure, requires both the preparation of geotechnical studies

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and inspections. Recent landfill constructions are those of Lemnos and Lesvos islands, for which the following geotechnical studies were carried out:

Stability checks for excavation of embankments and slopes, specifications of construction materials for both sealing and final covering, calculations of subsidence, and anchorages of sealing membranes.

In the field of sports, the foundation of the Peace and Friendship Stadium (PFS) presented important peculiarities. In specific, a drastic improvement of the soil was required to receive the loads of the foundations, since, beyond the bottom embankments at a height of 5 to 6 meters, the marine deposits were highly compacted. It was decided to load the soil with embankment and simultaneously carry out dynamic compaction to improve the soil. Dynamic condensation has had excellent results. The annular part of the floor plan of the closed stage was successfully founded on 160 well piles with a diameter of 1.3 m and a depth of 34 to 38 m.

In the closed stadium of Thermi Thessaloniki, pre-loading was applied with prefabricated drains for the foundation of a new Stadium to reduce the risk of liquidation and avoid excessive subsidence, while at the same time, the strength of the soil, in the form of load bearing capacity was improved.

In the field of culture, specifically in the mansion of the Friends of Music, the deep excavations that were necessary for the construction of an underground parking were an important design and construction topic. To support the ground, the classic "berlinoise" method was used with piles, prestressed anchors and shotcrete walls.

In the Cultural Center of the Stavros Niarchos Foundation, a high embankment was built with both a reinforced and unreinforced concrete section, a consolidation layer and gravel piles for the improvement of the foundation zone at the base of the reinforced section of the embankment [41].

Finally, it should be emphasized that while the science of geotechnical engineering is evolving rapidly, its future, according to many experts, is mainly focused on the following areas of work:

Waste management and environmental geotechnics, soil reinforcement, new techniques for soil improvement, field behavior of piles, computer applications to field observation, earthquake engineering and soil dynamics, effect of spatial variability of soil properties in seismic displacements of slopes, behavior of soft clay and stability analysis.

The general assessment, however, is that over time the fields of Soil Engineering will expand more and more.

5. Suggestions

The authors' attempt to document the history of soil mechanics and its diverse applications over the time is a painstaking research effort aiming at upgrading the teaching of the course. This course is actually taught not only to civil engineers but also to mining and surveyors as well as to agriculturists, geologists and scientists who deal in general with technical projects, and environmental infrastructure.

The purpose of the article is to establish the teaching of history for this course, in parallel with its basic principles, to both undergraduate and postgraduate students. In fact, it is proposed to create a virtual library in which each student, in addition to the great historical figures of geotechnical engineering, will be able to browse case studies through written texts, images and videos.

After all, gaining knowledge from important geotechnical constructions of both classical and modern times is probably the best way to achieve the objectives of the course.

6. Conclusions

1) From the above summary and research, it has been emerged that geotechnical engineering both in research and design but mainly in its application and construction has played and still plays an extremely important role for the infrastructure not only in Greece, but all over the world.

2) The development of Geotechnical Engineering up to about 1700 A.D. was through experimentation without a scientific character. It actually began to take shape from Coulomb's scientific discoveries in 1774 and has since evolved rapidly mainly from the period of Terzaghi.

3) However, according to the research effort of the authors of this article, the presence of geotechnical engineering is important not only in medieval times but also in antiquity, although the works were made by the existing craftsmen with empirical methods.

4) It is more than necessary to include in the material of Soil Engineering a special chapter that incorporates the history of the course. This chapter will arouse the interest of the students and the course will become more enjoyable.

5) Finally, the interesting applications of the above science in both building and infrastructure projects, which are described in detail in its historical course, increase both the knowledge of students along with their theoretical background and enhance their training.

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Contributions

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