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SOIL MECHANICS

CARL TERZAGHI: THE FOUNDER OF MODERN SOIL MECHANICS

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Based on the results of the research conducted by the authors, a short biography, creative achievements, and interesting facts about the life and work of one of the founders of soil mechanics as a science, Carl Terzaghi, are presented.

"A courageous, strong, and honest human being whose teaching, writing, speaking, and practice of civil engineering continue to light the way."
Ralph B. Peck

Fig. 1. Karl Terzaghi – Austrian and American geologist and civil engineer, one of the founders of soil mechanics.

Introduction

In the process of collecting material and writing a book by the authors on the design and construction of the Aswan Dam [1], the name of Karl Terzaghi who headed the international Board of Experts, familiar to all Russian geotechnicians, came up. An in-depth study of the activities of Karl Terzaghi revealed many interesting facts about his work as a researcher and engineer, some of which the authors considered necessary to introduce readers to in this article.

Short Biography

Karl Terzaghi (Fig. 1) was born on October 2, 1883 in Prague (Austro-Hungarian Empire). From 1900 to 1904 he studied at the Technical University in Graz. While undergoing compulsory military service for one year, he translated the famous English reference book on geology into German, and also significantly expanded it. After his service, Terzaghi returned to the university, where he lectured on geology and taught courses in road construction. His first scientific work on the geology of Southern Styria (Austria) dates back to the same time.

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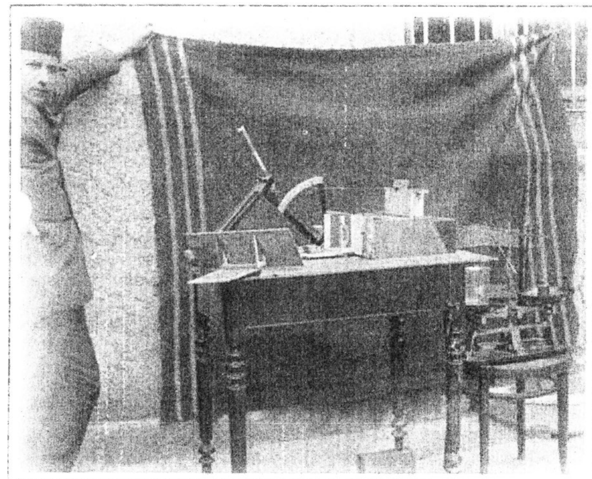


Fig. 2. Karl Terzaghi's apparatus for measuring soil pressure (Royal Ottoman College of Engineering).

Terzaghi's university activities gradually began to bring fame, and he decided to make a "trip" to the construction sites of some large dams in the United States. It allowed him to obtain a lot of valuable first-hand information.

In 1911-1912, Terzaghi worked as a consulting engineer at a number of sites in Russia, where he developed new methods for calculating industrial tanks, which formed the basis of his dissertation in 1912.

In December 1913, Karl Terzaghi returned to Austria, and after some time he was elected professor at the Ottoman Royal College of Engineering in Constantinople (now Istanbul Technical University).

Here began the most fruitful period in the scientist's life, dedicated to the main work of his life: the engineering understanding and use of soils as a construction material, whose properties could be measured by standardized methods. Using simple tools and equipment, he organized a laboratory and began active work. The results of his experiments and measurements, in particular the analysis of the forces acting on retaining walls, were first published in 1919 and quickly gained recognition.

Then he got a job at the Robert College of Constantinople, where he created his own laboratory. During this period, he studied various quantitative aspects of soil permeability and invented some new measuring instruments. At the end of many years of research, in 1924 Terzaghi published his main book, "Erdbaumechanik" ("Soil Mechanics"), which brought soil mechanics as a science to universal recognition [2]. This was followed by an invitation to work at the Massachusetts Institute of Technology, where he wrote several fundamental monographs on soil mechanics, including those translated into Russian [3, 4].

Laboratory Research in Constantinople

Karl Terzaghi was convinced that issues related to the problem of determining soil pressure on a structure could only be resolved through experiments. After arriving at the Ottoman Royal College of Engineering, he began searching for basic equipment that could be adapted for such experiments (Fig. 2). The inventory of his laboratory room consisted only of kitchen utensils, empty cigar boxes, scraps of steel and antique scales purchased at the market. And despite this, the experiments carried out using scrap materials are impressive!

The first question he decided to investigate was vertical and horizontal pressure in the soil. To do this, Terzaghi made a thick-walled wooden box and filled it with sand of a certain density. Specifying the vertical pressure was easy: it was necessary just to weight the sand. To determine horizontal pressure, Terzaghi placed three flat steel strips covered with paper between one of the box walls and the sand. One of these strips was attached to a string, which in its turn was attached to a laboratory scale so that its tension could be measured. An indicator was provided to detect the start of the steel strip movement. The results showed that the ratio of horizontal and vertical pressure in the sand at rest was 0.42. The results were the same regardless of sand density.

He was now ready to determine the force acting on the wall if it was allowed to move under the horizontal pressure of the sand. This is one of the fundamental points that a design engineer needs. Ingeniously using alternate rollers and sliders along the bottom of the box wall, he measured the horizontal force on a wall with and without horizontal friction. Based on the difference between these results, he determined the friction force magnitude. By introducing the friction coefficient, Karl Terzaghi was able to determine the magnitude of the vertical force acting on the wall.

Thus, Karl Terzaghi was able to achieve measurements both when the wall moved away from the sand ("active" case) and when it moved towards the sand ("passive" case). He continued his research, conducting several hundred different tests over three months, covering various wall angles, densities, and sand fill geometries.

On January 21, 1918, Karl Terzaghi gave a brief lecture at the Mathematical Society in Constantinople, outlining the ideas of his new theory, after which he was invited to make a presentation of his work.

Richard E. Goodman [5] writes that Terzaghi was nervous about the presentation. There was too much material, and there was still so much new in his head that he could not fit it all into the report. He forgot to describe some important points and spoke too quickly. However, a respected professor later said that listening to his lecture was like listening about Columbus's voyage.

After the report by Professor Philipp Forchheimer (1852-1933), an Austrian engineer, a pioneer in the field of civil engineering and practical hydraulics, who also contributed to the archaeological study of Byzantine water supply systems and introduced mathematical methodology into the study of hydraulics, creating the scientific basis for this field, a professor in Istanbul, Aachen and Graz, the most authoritative experts in the field of construction at that time, congratulated Terzaghi and noted his important and fundamental contribution to science. The work was published in 1919. A summary of it in English appeared a year later in Engineering News Record (ENR) 24, along with a paper on friction submitted to the Physical Review. Thus, the English-speaking world became acquainted with Karl Terzaghi.

Karl Terzaghi in Russia

A friend of Karl Terzaghi, who worked with a Russian contractor (J. J. Lorentzen & Sons) on the construction of a bank building on Nevsky Prospekt in the centre of St. Petersburg in 1911, reported that the construction of the foundation was unsuccessful; the contractor had no clear idea of how to fix initial mistakes. Terzaghi immediately offered his leadership of the project.

Initially, a retaining wall was installed along the entire perimeter of the pit to retain river sand, peat and fluid-plastic clays lying at the base of the foundations of this part of St. Petersburg. But it didn't do the job. Quicksand flowed like liquid through various cracks in the retaining wall that surrounded the foundation pit. As a result, neighbouring buildings were damaged, some of them were in disrepair.

"My first impression of what I saw left me with a dull, almost sphinx-like expression on my face." Three days later, after waiting for inspiration, he began to implement a dynamic plan. His solutions allowed the work to be brought back on schedule, completed on time, reducing the final cost by 30% with a workforce of one thousand people on day and night shifts.

After this, Terzaghi spent six months in Russia, where he developed some new graphical methods for calculating industrial tanks, which formed the basis of his dissertation, defended in 1912.

In 1929, Terzaghi visited Russia again. While in Moscow, he lectured on soil mechanics. He was pleased with the customers' willingness to follow his recommendations on testing for heavy loads and soil permeability when designing the Volga-to-Don Channel. He wrote to Lazarus White that *"despite the inconveniences of life in Russia, they are very enthusiastic about their professional activities."*

At the same time, in his typical manner, Terzaghi, paraphrasing a famous joke, wrote: *"If you have one Englishman, you have stupidity; two Englishmen, a Society; three Englishmen, a great people. With one Prussian* *you have nothingness; with two Prussians, an organization; and three Prussians, a military might. With one Russian you have a genius; with two Russians, confusion; and with three Russians, a public scandal."*

Terzaghi applauded the Russians for passing a law requiring centralized soil sampling and testing, field stamp testing, and uniform accounting of foundation characteristics for all Russian buildings. It was a measure which he tried unsuccessfully to introduce as a necessary step to improve the state of geotechnical engineering in the United States of America.

Analogue Method

Terzaghi visited New Orleans due to unusually large (approximately 25 cm) settlement at the Charity Hospital, which was built on piles resting on a load-bearing layer of sand. The engineers couldn't agree on what was happening. Terzaghi proved that this was consolidation compaction and showed that the sediments, essentially complete, are in remarkable agreement with the calculations of his theory. Since there was no adequate engineering guidance yet on how to apply consolidation theory to predict such settlements, Terzaghi wrote his own and included it in his final report.

However, since the building was unusual and unprecedented in certain respects, he recommended a reanalysis, offering the following statement about the limitations of judgment based on experience.

"When utilizing past experience in the design of a new structure we proceed by analogy and no conclusion by analogy can be considered valid unless all the vital factors involved in the cases subject to comparison are practically identical. Experience does not tell us anything about the nature of these factors and many engineers who are proud of their experience do not even suspect the conditions required for the validity of their mental operations. Hence our practical experience can be very misleading unless it combines with it a fairly accurate conception of the mechanics of the phenomena under consideration."

About Patents

Karl Terzaghi developed the design of drainage filters that solved the problems of dams in Algeria. Demand for this technology has been growing worldwide, both for their design and installation. One might expect that sooner or later some company would offer to license his patents. However, when he received such a proposal from Anton Grzy Winski, an engineer in Vienna, Terzaghi refused to cooperate, explaining that his filter eliminated only one of the many areas of uncertainty associated with dams, and he would not risk having his name ruined by someone else's failure.

He told Grzy Winski that the body of the dam could collapse without warning, taking with it the reputations of even those who had played only a small role. Therefore, he established a strict rule that his name could be used only if all preparatory work on the construction of the dam body was carried out under his personal supervision. Karl Terzaghi knew his worth and skilfully used his authority, since, not without reason, he believed that in the interests of clients he could find a better solution than anyone else.

Examination in England

In March 1938, an interesting "examination" of his knowledge was carried out in England.

Returning to Paris from North Africa, Terzaghi received a telegram from Siemens Bau Union, a firm-contractor in Berlin, with a request to help the branch in England solve the problem of constructing soil structures. On the morning of April 22, he called London and asked them for more information. A few hours later he was visited by Sir Robert Wynne-Edwards, the engineer for the construction of Chingford Dam No. 2.

The affable, fair-haired, blue-eyed Wynne-Edwards solemnly laid out the plans, profiles, and data on the wells. After examining them, Terzaghi asked where the dam was located, and was told that it was fourteen miles north of London, to which Terzaghi immediately responded: *"That dam must have been designed by an enemy of the British nation because it will fail, whereupon your Parliament and Westminster Abbey may be washed into the Thames."* Now the visitor smiled as he reported that it had already failed. Terzaghi asked what instructions he received from his boss. The reply: *"To watch your face while you look at the profiles. If*

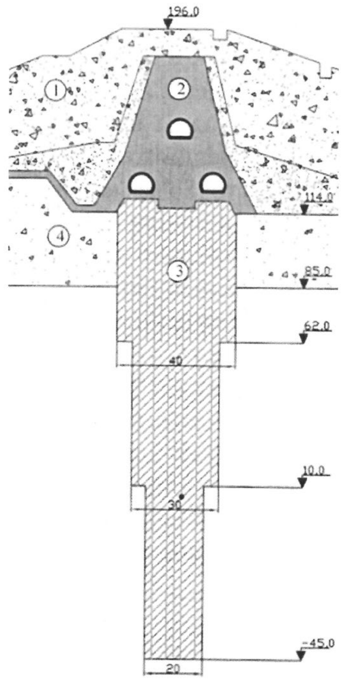


Fig. 3. Design of an anti-filtering curtain: 1) rockfill dam; 2) clay core; 3) curtain; 4) shellal sand.

you don't show any signs of disapproval, I should take my hat and go. If you are shocked, I should put you into an airplane and bring you over."

The Chingford Dam was supposed to be an embankment 5.5 km long, the estimated height of which varied from 11 to 13 m. With the achieved embankment height of only 7 m, a twenty-meter-wide dam was supposed to settle by 70 cm and move by 4 m.

To find out where the weak soils were located, Terzaghi proposed an unusual plan: build the entire length of the dam in accordance with the original plan until a separate part of the dam begins to lose stability. This would define the actual local bearing capacity of the base of a long structure, which most likely varied greatly from point to point. That would allow the design solution to be adapted to real conditions and save a lot of money. Unfortunately, this turned out to be impossible. Ultimately the project was delicately modified under his leadership.

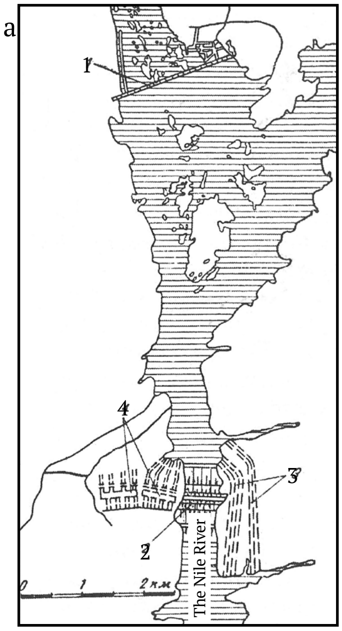
Aswan Dam

The Aswan Dam is one of the grandiose buildings of the 20th century. In accordance with the project, the dam height above ground level was 111 m, and the total height together with the anti-filtering curtain was more than 250 m (Fig. 3). There were no precedents for the construction of such high dams on fine-grained river sediments under significant hydraulic loads [5].

The development of this grandiose project required international funding and highly qualified engineers. It was planned to attract leading European design organizations and create a Board of International Consultants (hereinafter referred to as the Board).

Karl Terzaghi was invited to work on the Board and began the work in Cairo in 1954. Terzaghi convinced his colleagues that first of all it was necessary to drain the construction site. To do this, he proposed building seven tunnels in the surrounding rocks, 16.5 m in diameter and 2.6 km long.

In June 1959, Egyptian President Gamal Abdel Nasser entered into an agreement to carry out work on the first stage of construction with the Soviet Union.



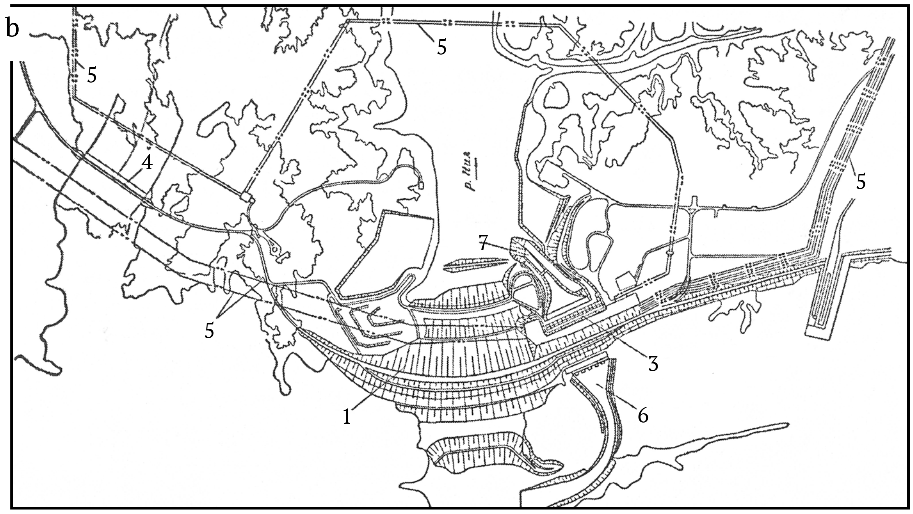


Fig. 4. Layout of the dam: a) developed by Jib, an English company, b) developed by the Hydroproject Institute; 1) high-rise dam; 2) drainage tunnels; 3) hydroelectric power station; 4) emergency spillway; 5) power lines; 6) upstream channel; 7) downstream channel.

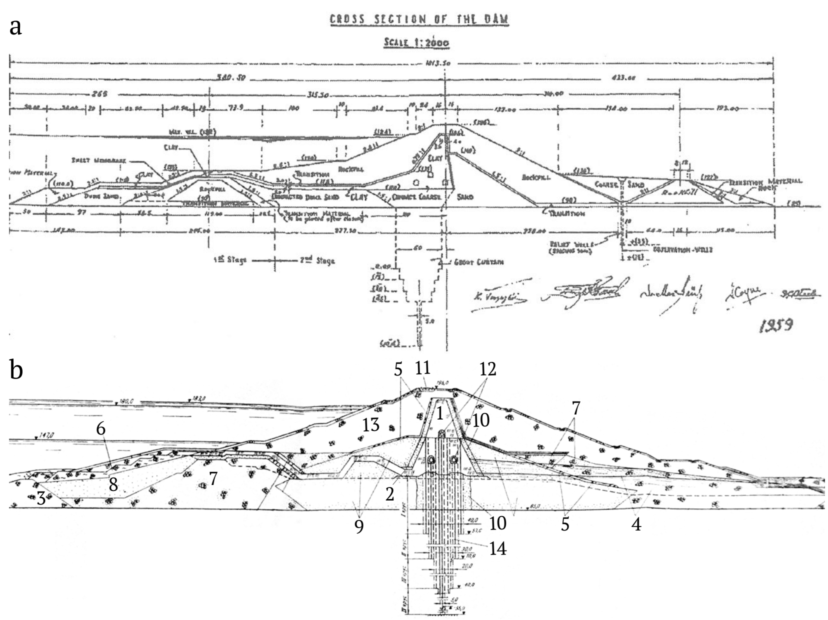


Fig. 5. Cross-section of the dam according to the projects: a) of the Board of International Consultants under the leadership of Karl Terzaghi, b) of the Hydroproject Institute; 1) clay core; 2) plastic clay; 3) rock mass; 4) rock mass washed up by sand; 13) compacted rock mass; 5) crushed stone; 6) stone washed up with low-filtration material; 7) stone washed up with sand; 8) dune sand; 9) compacted dune sand; 10) coarse sand; 11) road with asphalt concrete pavement; 12) injection galleries; 13) wells of the anti-filtering curtain; ----) the stage I dam outline.

Soviet engineers proposed improving the design solution to reduce the time and cost of work. First, it was proposed to replace seven drainage tunnels with one open channel (Fig. 4). Secondly, it was proposed to combine the spillways and hydroelectric power station into one structure, concentrating concrete and tunnel work in one place. Thirdly, it was proposed to exclude the enormous work volume of filters installation under water to a depth of 35 m between sand and rock fill due to washing up the cavities between the stones with dune sand (Fig. 5).

Fig. 6. General view of the Aswan Dam, 2021.

Karl Terzaghi was critical of all changes to the design solution. He was convinced that abandoning the seven tunnels was a reckless decision, motivated by the fact that the USSR lacked both the equipment and experience to organize a large-scale project to lay tunnels for the spillway. The Board, led by Terzaghi, unanimously rejected the changes to the project proposed by Soviet scientists. Construction of the dam from the sides to the middle, in their opinion, should have led to uncontrolled cleaning of the area of the dam base below the overlap area and significantly complicate the construction of the main dam. The removal of the sand filter in favour of a layer of stone backfill, the voids of which were to be filled with sand, worried Karl Terzaghi. He wrote: *"While laying the stone embankment continues, sand will be washed into the voids of the embankment. There is no practical means of determining which parts of the rock embankment remain unwashed... this could lead to the destruction of the dam"* [5].

Due to strong disagreement with the work being carried out by the USSR, Terzaghi was forced to resign. In his resignation letter, he wrote: *"The upstream cofferdam may, and probably will, serve its function as a construction expedient during the first stage even in the event that all the recommendations of the Board are disregarded. However, after the dam is completed and the reservoir is filled, the service conditions of the cofferdam are entirely different from what they were during construction. As a consequence, the cofferdam may then start to deteriorate, rapidly or slowly, and at that stage it may even be impracticable to stop the process. Radical departures from the Board's well-considered recommendations concerning design and construction of the upstream cofferdam involve such a possibility. Therefore, I owe it to my professional reputation to discontinue my association with both the first and the second stage of the project"* [2].

It should be noted that recently a group of Russian geotechnical engineers and architects visited the dam (Fig. 6) [1]. Inspection of the condition of the dam and its uninterrupted operation for decades proved the correctness of the design solution developed and implemented by Soviet engineers. No defects were found either on the lower or on the upper pools. The operation of the hydroelectric power station has not stopped since its launch in 1971. It confirmed the correctness of the design solution and the work quality and refuted the conclusion of Karl Terzaghi.

Accidents in Geotechnics

In the early 1960s, in France (in Fréjus, near Ruth on the French Riviera), a dam collapsed, killing more than 400 people. The dam failed during the initial filling of the reservoir due to insufficient strength of one of the rock abutments of a very thin concrete arch. Later, Karl Terzaghi would sharply criticize the decision to build such a structure on a geologically unsuitable site. But then he consoled his distraught colleague by writing that *"failures of this kind are, unfortunately, essential and inevitable links in the chain of progress in the* a b

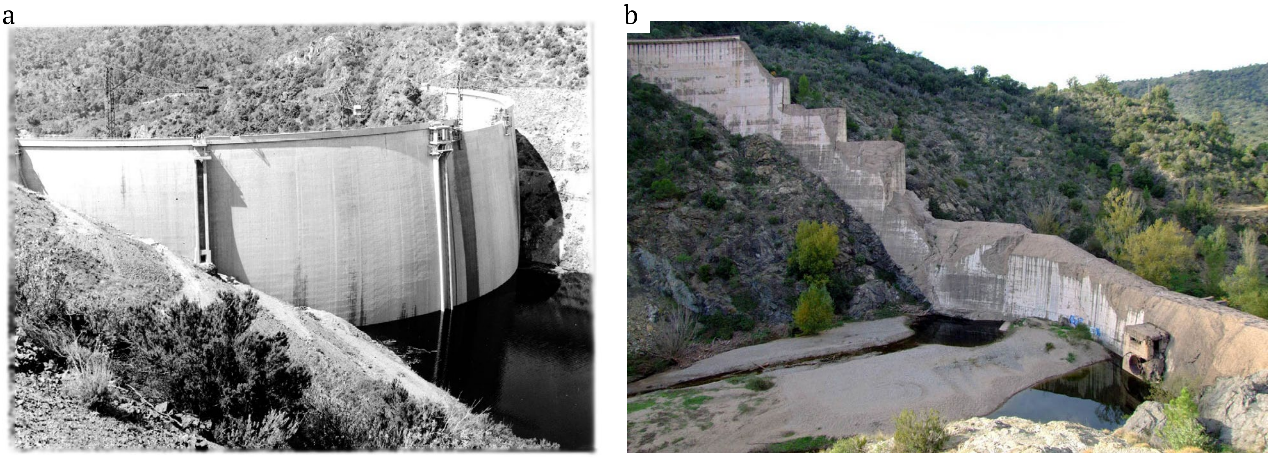


Fig. 7. Malpasset Dam in Fréjus (French Riviera): a) before the accident, b) after the accident.

realm of engineering, because there are no other means for detecting the limits to the validity of our concepts and procedures.... The torments which you experienced should at least be tempered by the knowledge that the sympathies of your colleagues in the engineering profession will be coupled with their gratitude for the benefits which they have derived from your bold pioneering" [5].

About Mathematics

Terzaghi's closest friend and comrade, R. B. Peck, in his article "Karl Terzaghi, 1883-1963. Thoughts occasioned by the centenary of his birth" [6] wrote that Terzaghi understood from the very beginning that a solid theoretical basis is essential for the progress of engineering, and he himself contributed a lot to the creation of this basis. However, no less important is knowledge of the physical properties of soils to which the theory is applied, and, above all, verification of theoretical calculations by field observations. He was afraid that pure theorists could cause irreparable damage to soil mechanics, since it was easier and more pleasant for them to continue to develop their theories than to follow the slow, painful, and sometimes disappointing results of a critical comparison of calculations according to the accepted theory with the reality of field observations.

Here is one of his jokes about mathematicians: "Mathematicians are useful animals who should be kept in a golden cage and fed with problems in moderation."

And at the end of the article the authors would like to quote Karl Terzaghi, with which he ended the James Forrest lecture in 1939: *"I cannot help but feel deeply concerned about the arrogance generated in many representatives of the coming generation of engineers, because ... there is a tendency among the young and inexperienced to blindly believe in formulas (programs), forgetting that most of them are based on premises that are not very accurately reproduced in practice, and, in any case, often cannot take into account side effects, which only can be predicted using observation and experience, and common sense makes it possible to take into account."*

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