Observation, Quantification, and Judgment: Terzaghi and Engineering Geology

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Abstract: A review of Terzaghi's published and unpublished papers and notes made it possible to trace his way from geology over geotechnical engineering to engineering geology. Not only does this reflect his career, it also is the path which led him from observation to quantification to judgment and culminated in the integration of these three components in his concept of engineering geology and, specifically, in the observational method.

Introduction

Terzaghi's work never failed to impress me. Over the years I became also increasingly fascinated by his approaches to problem solving. A Terzaghi Fellowship from The Norwegian Geotechnical Institute (NGI) made it possible for me to spend several weeks sifting through the wealth of documents in the Terzaghi Library. One is immediately struck not only by the volume of material but how well organized and meticulously Terzaghi documented his professional life, in the form of diaries, notes, reports, and supporting material for lectures. Bjerrum in his introduction to *From Theory to Practice in Soil Mechanics* (Bjerrum 1960) commented tongue-in-cheek on Terzaghi's concern for "his well-organized piles," which NGI transformed into a library. What makes going through Terzaghi's work a real pleasure is not only the information per se but the fact that his abilities as a writer and raconteur pervade his most technical writings. What was of particular interest to me, and what I shall try to briefly describe next, is Terzaghi's relation to geology, which not only made him the founder of geotechnical engineering but also one of the first teachers of engineering geology.

Geology

As Terzaghi describes in "Mein Lebensweg and meine Ziele," which he wrote in 1937, he became interested in geology during his studies at Graz and became really enthusiastic about it through observations during his many mountain trips. His first publication in the area was a translation into German of Geikie's *Outlines of Field Geology* (1906) with which he evidently kept himself busy on guard duty and during lengthy incarcerations, during his one year military service. As a matter of fact, he not only translated but expanded the booklet in a number of areas (karst, glacial geology). His first employment very quickly involved him in work that today would be called typical geotechnical engineering. It seems that, in addition to his interest in applying geology to engineering problems, Terzaghi always had an interest and love for geology itself, and he approached it with the same scientific, rational thinking as his geotechnical work.

During hydrographic and geologic reconnaissance for a power plant in

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Note. Discussion open until April 1, 1992. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on October 29, 1990. This paper is part of the ***Journal of Geotechnical Engineering***, Vol. 117, No. 11, November, 1991. ©ASCE, ISSN 0733-9410/91/0011-1772/$1.00 + $.15 per page. Paper No. 26379.

the Croatian Karst in 1909 he developed an initially hotly debated but later accepted explanation for the geomorphologic evolution of poljes (1913 and 1958) and of typical slope inclinations. (*Poljes* are steep-walled, flat-bottomed depressions in karst terrain.) In particular, he related the rate of CO_2 production in forested areas, as compared to denuded areas, to the differences in limestone solution. He concluded that poljes represent elevations where periodic inundation eliminated the forests, which in turn led to a reduction of the rate of limestone solution. With regard to slope angles he observed the remarkably narrow range between 30 and 34° of slope inclinations of forested slopes. This is the angle at which a soil cover has a constant thickness of about 1 m because there apparently is a balance between the rate of limestone solution producing residual soil, and gravity and erosion effects removing the soil.

Fifteen years later (1924) in his lecture at Robert College in Istanbul on drift of continents he reached conclusions that went beyond Wegener's (1915) and approach those of plate tectonics. Based on statistics of sea-floor and land-surface elevation and on data on sea-floor and continental rock density, combined with the notion of isostatic compensation, he recognized the existence of continental plates (although not using this term). Based on an extensive literature study, he discussed the similarity of lithology, of major structural features and of fossils in South America and Africa as well as in India and Australia, respectively. In the preparatory notes for the lecture he also studied the viscosity-depth relations of the *sima* (silicon-magnesium rock) outermost in oceanic crust and underlying the sial (silicon aluminum) rocks of the continental crust, and of faulting in relation to spreading mechanisms. In his lecture on analysis and opinion in geology (1928) he added ideas on convection currents as a driving mechanism. There are also statements in the 1924 lecture which are incomplete or partially incorrect in view of today's knowledge. It is amazing, however, how close he came with his interpretations to putting the entire picture together. While Terzaghi was thus always trying to find rational explanations for geologic features and phenomena, he also thrived on simply observing nature. He therefore regretted not having seen the Panama Canal landslides in full activity during construction of the Canal or the fact that during his Central America trip in 1928 the slides along the Northern Railway of Costa Rica did not move. He compensated for this to some extent by having a Costa Rican Massachusetts Institute of Technology (MIT) student accompany him to the top of the Poas Volcano where they had "an unusually clear view over the continental divide and the lively doings at the bottom of the crater" (Terzaghi 1928).

We have thus seen that keen observations and scientific interpretation played an important role in Terzaghi's relationship with geology. Judgment and geology became tied to each other as the years went on, and as he realized the limitations imposed by nature on the application of his theories.

Observation

Maybe these comments should be entitled "observation and learning from experience." Terzaghi's "notes on construction 1912/13" in which he describes his visits to construction sites in the Western United States include as much material extracted from publications as from his own observations. The fact that he studied the documentation about these construction sites in preparing his trip illustrates both a fundamental requirement for good observation and Terzaghi's approach. Only by being fully prepared can one really gain from observation. The "notes on construction" that he also continued later (see also "Quantification" later) were by no means restricted to geologic aspects of construction. They range from production rates, to load capacity of ropes, to swell ratios of different rocks after blasting, to comparisons of bid and actual construction costs, and they include not only organizational and technical details but also reach beyond the particular project. For instance, when describing the repair of a levee failure on the Mississippi between New Orleans and Baton Rouge (Hymelia Crevasse) he gave a detailed description of the closing operation, but also discussed estimates on the losses caused by flooding of farmland in relation to the repair cost, and all this was put into the context of the history of the Mississippi River regulation (flow volume, levees built); this in turn was put into the context of the development of the U.S. gross national product.

An example may further illustrate Terzaghi's approach to observation. On his tour of U.S. construction sites in 1912/13 he got himself hired as driller on the Big Eddy Lock Project (Columbia River). His notes read like a drilling instruction manual, including a step-by-step description from collaring to production drilling, a discussion of how to deal with mishaps (e.g., lost drill stems or wedging by loose rock), and details of the entire machine and its maintenance. Production rates and cost are also given. But then comes the critique. He notices the heavily disturbed rock conditions in the section worked on by his contractor as compared to those in another contractor's section, although the rock is the same. He thinks of other arrangements of the drill holes and of lower blast loads.

Learning from observation and past experience requires not only a willingness to absorb information but the capability to transmit it. In a letter to his grandfather, prior to his trip to the West, Terzaghi admitted to having had an aversion against study trips but convinced himself of the necessity to undertake one. Why this happened becomes clear in his request for financial support of his trip to the Austrian Society of Engineers and Architects (this support never materialized, however). He stated that reports on engineering publications usually register the state of completion of each project but give only cursory coverage to mishaps and neglect to report the "obvious" such as settlements, permeability, and effect of temperature.

Five years later he wrote an article about this in the journal of the Austrian Society of Engineers and Architects and 25 years later, in his presidential address to the First International Conference on Soil Mechanics and Foundation Engineering, "Relation between Soil Mechanics and Foundation Engineering" (Terzaghi 1936), he commented on the problems of information transmittal:

> One of the outstanding impressions which I got while preparing the abstracts of pre-war publications was that of a steady decline of the capacity for careful observation after the eighteen-eighties. Prior to about 1880 a surprisingly great number of stimulating field observations were published by engineers. However, after the eighties, the interest in observing and describing the whimsical manifestations of the forces of nature seemed to fade out. I am inclined to explain this decline by a growing confidence, produced by the inertia of the human mind, in the theories concerning the behavior of earth. At the time when the theories originated, their authors were still keenly aware of the bold approximations involved, and nobody thought of accepting

them at face value. As the years passed by, these theories were incorporated into the stock of knowledge to be imparted to students during the years of their college training, whereupon they assumed the character of a gospel. Once a theory appears on the question sheet of a college examination, it turns into something to be feared and believed, and many of the engineers who were benefitted by a college education applied the theories without even suspecting the narrow limits of their validity.

QUANTIFICATION

When going through Terzaghi's notes on construction from 1915, which are all annotated and abstracted articles from journals and book chapters, one notices an interesting fact. Some of the notes are organized by "geology"; typical headings for each of these note-sets are "Gründungsarbeiten im sandigen Flachland" (foundation works in sandy planes) and so on. Another group, however, shows set headings such as "Porenvolumen und Festigkeitseigenschaften" (pore volume and strength properties), "Klassifizierung der Bodenarten nach Gewinnungsfestigkeit" (soil classification based on excavatability), "Eignung der Gesteine zu Baumaterialien" (suitability of rocks as construction materials), "Widerstand gegen das Eindringen von Pfählen" (resistance against penetration of piles), and "Klüftigkeit der Gesteinskörper" (jointing of rock).

Quite obviously, the direct "empirical" relationship between geology and engineering had become unsatisfactory. As a matter of fact, Terzaghi had tried to develop such relationships using the wealth of data collected on this 1912 trip to the West while he was on his second job during this trip (in Portland, Oregon). As he stated in his "Lebensweg," he was greatly disappointed that "geologically identically described layers behaved differently with regard to bearing capacity, permeability and other technical characteristics."

Not only the empirical relationships were unsatisfactory, but also the available theories. In the aforementioned notes on construction one finds also extensive and detailed summaries of earth-pressure theories including theories for earth pressure around tunnels. As he stated, the theories were inadequate because they dealt with the limiting state only and not with the preceding deformations. The relationship between geology and technical performance needed to be quantified, and this had to be done by simultaneously developing experimentation and theory to capture the underlying mechanics.

What followed is widely known. Initially at the Ottoman Engineering University and then at Robert College in Istanbul, Terzaghi created soil mechanics.

What is important to note is the simultaneity of contributions to basic mechanics (Terzaghi 1920a, 1923) and to geotechnical engineering (Terzaghi 1920b, 1921a, 1922). [For a complete listing of Terzaghi's publications up to 1960, see, e.g., *From Theory to Practice in Soil Mechanics* (Bjerrum et al. 1960).]

Terzaghi never lost sight of practical applications and, therefore, his answers to the basic questions resulted in the solution of engineering problems. This capability to see the essentials also explains why the experiments could be made with relatively simple instruments. As Terzaghi said in his "Lebensweg," "The success of research does not depend on the completeness of the experimental equipment but on the truth underlying the concept." It must be said, however, that in spite of the apparent simplicity of the laboratory equipment it involved numerous innovative aspects such as the indirect measurement of earth pressure. Terzaghi was also fully aware of what degree of precision was necessary, and he found the means to measure on the micron level (Terzaghi 1920a).

Quantification for engineering purposes involves the basic mechanisms on the one hand, as well as the relationships between several of these basic mechanisms and the behavior of an engineering structure in the geologic environment. From a practical point of view equally important is the third aspect, the transmittal of information on physical relationships to the client and to future engineers. Not surprisingly, Terzaghi addressed this issue in "Die physikalischen Grundlagen des technischen geologischen Gutachtens" (Terzaghi 1921) (The physical basis of geotechnical consulting reports) and in "Technisches Unterrichtswesen" (1921c) (Technical Education).

Judgment

There is no better way to describe the role of judgment than with three quotes from Terzaghi's writings that are given in reverse temporal sequence. Terzaghi, who created soil mechanics by giving it a theoretical basis, said in his presidential address at the Third International Conference on Soil Mechanics and Foundation Engineering (Terzaghi 1953): "There was only one temporary deviation of the line I pursued. It involved a brief period, in the twenties, during which I believed that the problems of earth work and tunnel engineering like those of bridge design could be solved by theory alone, on the basis of the results of adequate laboratory tests." The "pursued line" he was referring to is that of relating engineering and geology. He then goes on to say, "However, in our field, theoretical reasoning alone does not suffice to solve the problems which we are called upon to tackle. As a matter of fact it can even be misleading unless every drop of it is diluted by a pint of intelligently digested experience".

In his lecture on the "Actual Factor of Safety in Foundations" given in 1934 (Terzaghi 1935) before the Institution of Structural Engineers in London, he says toward the end of his talk, "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."

And in 1917 ("Die Unzulänglichkeit veröffentlichter Baubeschreibungen"), (Terzaghi 1917) "Mature judgement only becomes clear foresight after it has been applied in a critical review of the experience and observations of others."

Judgment is thus the intelligent use of experience or, more cautiously expressed, it is the recognition of one's limitations, of the limitations of the methods one uses, and of the limitations and uncertainties of the materials one works with; and this brings us back to geology.

Engineering Geology

Terzaghi went full circle from trying to directly relate geology and engineering, to establishing basic physical relationships, and finally to "Examining the array of useful knowledge which has filtered into my own system and crystalized into sound judgement, I find that it contains one ounce of geology for every pound of theory of structures and soil mechanics". (Terzaghi 1957). Also, his teaching first of soil mechanics at MIT (1926–29) and then of engineering geology at Harvard (starting with his proposal in 1938, "Suggestions for a Course in Engineering Geology") seems to follow this sequence. This would be a superficial assessment. As a matter of fact, geology never ceased to be the context in which Terzaghi placed his work. Most telling in this regard, besides his consulting reports, is the fact that the publication of "Erdbaumechanik auf bodenphysikalischer Grundlage" (Terzaghi 1925) and "Principles of Soil Mechanics" (Terzaghi 1926) was followed shortly thereafter (in 1929) by three chapters (250 of 680 pages of text) in "Ingenieurgeologie" by Redlich, Terzaghi, and Kampe (1929) and the famous "Effect of Minor Geologic Details on the Safety of Dams" (Terzaghi 1929), not to mention the previously mentioned account of his trip to Central America in 1928. Comments on geology were always central in his addresses to the International Conferences on Soil Mechanics and Foundation Engineering (Terzaghi 1936, 1948, 1953, 1957).

What emerges from all this is expressed in Terzaghi's two 1961 papers "Past and Future of Soil Mechanics" (Terzaghi 1961b) and "Engineering Geology on the Job and in the Classroom" (Terzaghi 1961a): The geotechnical engineer should apply theory and experimentation but temper them by putting them into the context of the uncertainty of nature. Judgment enters through engineering geology.

In the 1961 soil mechanics paper, Terzaghi (1961b) also introduces the term and examples for the now well known *observational procedure*. There is no better summary of Terzaghi's life than this procedure, which is a rational combination of theoretical predictions and observations to deal with nature's uncertainties.

Acknowledgments

A Terzaghi fellowship given to me by NGI made it possible to do the research in the Terzaghi Library and to write this paper. I would like to thank Dr. Kaare Hoeg, Director of NGI, for this and also for being the keeper of the Terzaghi Library. I would like to thank Dr. Ruth Terzaghi and Professor Ralph B. Peck for their comments.

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