Hydrogeology and engineering geology in the education of geotechnical and geoenvironmental engineers

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ABSTRACT
Engineering geology and hydrogeology are both essential components of the formal education of geotechnical and geoenvironmental engineers. Unfortunately, the teaching of these subjects to undergraduate civil engineers has become very limited and that which is taught is biased towards elementary physical geology, which is of limited value. This trend is likely irreversible and is completely at variance with what Terazaghi and Legget recommended before 1980. The role of these subjects in the teaching of civil engineers is discussed on the basis of the need to defer teaching the applied earth sciences – engineering geology, geomorphology and hydrogeology – until the final undergraduate year or, better still, the first year of graduate education. Fortunately, developments within civil engineering education make this a possibility in the next ten years, most likely for those who are likely to specialise in geotechnical and geoenvironmental engineering.

RÉSUMÉ
Géologie de l'ingénieur et de l'hydrogéologie sont deux composantes essentielles de l'éducation formelle des ingénieurs en géotechnique et géo-environnemental. Malheureusement, l'enseignement de ces sujets au premier cycle en génie civil est devenue très limitée et ce qui est enseigné est orientée vers la géologie physique élémentaire, qui est d'une utilité limitée. Cette tendance est probablement irréversible, et est totalement en contradiction avec ce que Terazaghi et Legget recommandé avant 1980. Le rôle de ces sujets dans l'enseignement des ingénieurs du génie civil est discutée sur la base de la nécessité de différer l'enseignement des sciences appliquées de terre - géologie de l'ingénieur, la géomorphologie et hydrogéologie - jusqu'à la dernière année de premier cycle ou, mieux encore, la première année d'études supérieures . Heureusement, l'évolution dans l'enseignement du génie civil que cette possibilité a dans les dix prochaines années, le plus probable pour ceux qui sont susceptibles de se spécialiser dans l'ingénierie géotechnique et géo-environnemental.

1 INTRODUCTION

Specialization leads to increasing differentiation of knowledge and, while essential for technical progress, this same specialization means that broad knowledge of related fields is forfeited (Sellers, 1994). Specialization within civil engineering has resulted in the decline of teaching of geology to engineers (e.g., Rogers, 2002) thus affecting the working relationships of both engineering geologists and hydrogeologists with geotechnical and geoenvironmental engineers through an absence of common working knowledge. Medley (2009) has pointed out that "*with the evolution of academic and technical specialization, the "Geo" understanding in "Geotechnical" is now so diminished and removed from "technical" that most Geotechnical Engineers need Geological Engineers and Engineering Geologists to tell them what, just a few years ago, they likely knew for themselves."*

Both British and American engineering geologists have worried about the place of engineering geology in geo-engineering projects in recent years (e.g., Knill, 2003; Hatheway, 2006,). John Burland (2007), Professor of Soil Mechanics at Imperial College, London, has pointed out that 90% of failures arising from geotechnical design decisions are due to "*a lack of knowledge about the ground profile – often the groundwater conditions*", i.e., the site investigation was inadequately conducted. Furthermore, landslide susceptibility is seldom addressed in the context of the groundwater flow system in which the particular slope is situated. Therefore risk reduction in geotechnical engineering must mean a closer integration of engineering geology and hydrogeology with geotechnical engineering.

Since 1980 hydrogeology has undergone a change of remarkable nature as contaminant hydrogeology developed as a recognizable sub-discipline that has vastly expanded the population of hydrogeologists. Groundwater contamination issues, arising from waste disposal, mining, past releases of solvents and fuel hydrocarbons and brownfields redevelopment, are of very great importance to geoenvironmental engineers. To design remediation systems that address the fate and transport of groundwater contaminants requires a detailed knowledge of the groundwater flow system that is contaminated. Therefore risk reduction in geoenvironmental engineering must mean a closer integration with contaminant hydrogeology.

Consequently, engineering geology and hydrogeology are both essential components of the formal education of geotechnical and geoenvironmental engineers. Unfortunately, the teaching of these subjects to civil engineers is very limited and biased towards general physical geology rather than engineering geology and traditional seepage problems rather than a broader analysis of flow systems. Thus any "Body of Knowledge" analysis of the educational foundations of geotechnical and geoenvironmental engineers should include engineering geology, geomorphology and hydrogeology instruction and field trips so that the complexity of natural geological environments and the uncertainties involved in the quantitative approximations necessary for engineering designs are better understood by those responsible.

2 ENGINEERING EDUCATION AND THE APPLIED EARTH SCIENCES

I use the term "Applied Earth Sciences" to signify the disciplines of engineering geology, geomorphology and hydrogeology. As Medley (2009) has observed it is a "graceful" term that connects the geological sciences to the practice of geotechnical and geoenvironmental engineering through soil and rock mechanics.

In his 2002 analysis of the teaching of the geological sciences to civil engineers, J.D. Rogers of the University of Missouri-Rolla reported that in the USA "*only 4% of the accredited civil engineering programs require their undergraduates to take a course in engineering geology."* Rogers (2002) explains that within civil engineering the practice of geotechnical engineering has become a speciality and "*geotechnical aspects of civil engineering are usually performed by external consultants".* Therefore, because Rogers reports that only 9% of civil engineering graduates find work in geotechnical engineering, there is little place for the teaching of the applied earth sciences in today's civil engineering curricula.

Compare this situation with what Robert Legget and Karl Terzaghi stated was required of the education of a civil engineer (cited by Proctor, 1981) of an earlier time:

"...a basic part of the training of every civil engineer must be an introduction to the science of geology, preferably in a manner that will illustrate the relevance of geology to civil engineering" (Legget, 1979); and

"*I believe that a two-semester course combined with field trips fully serves its purpose provided that the course represents the combined efforts of a geologist who appreciates the requirements of engineers and an engineer who has learned from personal experience that geology is indispensable in the practice of his profession*" (Terzaghi, 1957).

Unfortunately, since 1975, there has been a marked disappearance of the applied earth sciences from the required curricula of civil engineering students and a failure to replace faculty who taught engineering geology (Rogers, 2002), e.g., Jahns at Stanford, Kiersch at Cornell and, most famously, Terzaghi at Harvard. During this same period, hydrogeology has blossomed and most geology departments now employ at least one hydrogeologist and most civil engineering departments give courses in groundwater hydrology.

The report by the American Society of Civil Engineers *Civil Engineering Body of Knowledge for the 21st Century: Preparing the Civil Engineer for the Future* (ASCE, 2008) – known as "BOK2" – exemplifies just how far current thinking in civil engineering education has evolved from that of Legget and Terzaghi. The discussion of the natural sciences in BOK2 relegates the applied earth sciences to a minor supporting role after physics and chemistry: "*Additional breadth in such natural science disciplines as biology, ecology, geology/geomorphology, et cetera is required to prepare the civil engineer of the future."*

Thus, it would appear that the teaching of hydrogeology has gained at the expense of engineering geology in many universities and colleges. This is less the case in Canadian than in American universities, probably because of the initial effect of Robert Legget in Canadian geotechnical practice, then the later effects associated with the continuing development of large-scale urban infrastructure, dam building and mining development in Canada that created economic conditions in Canada after World War II not dissimilar to those that brought Terzaghi to America before World War II.

It is also likely that there has been a profoundly beneficial integrating effect produced by the Canadian Geotechnical Society (CGS), which has practice-oriented divisions of Rock Mechanics, Engineering Geology and Hydrogeology as well as other geotechnical and geoenvironmental divisions. While exposure to related geotechnical disciplines at CGS meetings may be most helpful in showing the "common ground" of the geo-engineering profession, a common language is best begun at the university level through coursework and field trips as Terzaghi recommended.

The few universities that have both Civil and Geological Engineering undergraduate programmes often require that first-year Civil Engineering students take a course in elementary geosciences, e.g., Colorado School of Mines, the University of Wisconsin-Madison and the University of Waterloo. An unintended consequence of a first-year introductory course is that some engineering students switch their field of intended study from civil to geological engineering and form a significant proportion of the geological engineering class.

However, an elementary course can in no way compensate for a more advanced course at the fourth-year level – or later in graduate school – after the student has studied calculus and the mechanics of soils, fluids and materials so that geological processes and materials can be treated at a more advanced level befitting civil engineers.

3 GEOTECHNICAL TEAMS

The relationship between geotechnical engineers and engineering geologists, who are often their team partners, has been a matter of concern in the USA (Sitar, 1985), Canada (Hungr, 2001), Europe (Bock, 2006) and in particular in the UK (Knill, 2003). This concern has often to do with the roles that geotechnical engineers and engineering geologists play in particular projects and how they act collaboratively. Schematics that show the roles played by geotechnical engineers -- those practicing rock mechanics and soil mechanics -- and engineering geologists usually involve a triangular relationship of mutual interdependence.

But in the UK, John Knill (2003), late Professor of Engineering Geology at Imperial College, wrote of his regret that engineering geology was not considered by geotechnical engineers as being of equal importance to them as were soil and rock mechanics.

If Knill was correct -- and correct perhaps not just with respect to the UK -- then it is likely that geotechnical project managers have failed to heed the wisdom of the founders of geotechnical engineering. For example, Karl Terzaghi wrote of himself in 1961 that "*as his experience in the practical application of soil mechanics broadened, he realized more and more the uncertainties associated with the results of even the most conscientious subsurface explorations. The nature and importance of these uncertainties depend entirely on the geological characteristics of the sites*" (cited by Sitar, 1985). Here then Terzaghi points to one cause of failure in the design of infrastructures, i.e., the complexity of geological phenomena even at the site scale.

Geotechnical teams must be carefully balanced and skilfully led while maintaining the flow of information between members during site characterization, experimental testing and numerically-based design. A former aerospace engineer, James Adams of Stanford University, notes this about design teams "*The team must be large enough to include the necessary knowledge and skills but small enough to take advantage of the high quality of communication, creativity, and motivation found in small work groups....there is no more rewarding job than being part of a motivated multidisciplinary design team working on a challenging and important product*" (Adams, 1991).

According to John Burland (2007) "*four distinct but interlinked aspects*" define geotechnical practice:

1. The ground profile including groundwater conditions;
2. The observed or measured behaviour of the ground;
3. Prediction using appropriate models; and
4. Empirical procedures, judgement based on precedent and 'well-winnowed' experience.

It is the failure to follow these four principles that lead Burland to observe that 90% of failures arose from a lack of knowledge of site conditions and that it was often the groundwater conditions that caused failure.

In his recent book on the career of Rudolph Glossop, a founder of both the Quarterly Journal of Engineering Geology and Géotechnique, Williams (2010) presents an excellent example of this point. He describes the difficulties that Glossop faced during the construction of the Derwent Dam in north-east England in the 1950s that were due to inadequate site characterization of the hydrogeological conditions associated with glaciofluvial sands and gravels that had not been accurately established.

Therefore we can visualize geotechnical project teams being composed of individuals with competence in the following professional disciplines (Hungr, 2001):

a) Engineering and environmental geology;
b) Geomorphology;
c) Geoenvironmental engineering;
d) Geological engineering and rock mechanics;
e) Geotechnical engineering including soil mechanics and foundation engineering; and
f) Hydrogeology

But how are they to communicate if there is no shared technical language for discussion to facilitate working in Morgenstern's (2000) 'Common Ground'?

TABLE 1: PROFESSIONAL COMPETENCIES OF GEOTECHNICAL ENGINEERS (after BOCK et al., 2004)

Specialized testing methods	Understand the use and reliability of (1) lab testing instruments, e.g., triaxial testing machines and oedometers, and (2) field procedures for estimating parameters, e.g., slug tests to measure hydraulic conductivity
Constitutive laws	These laws define the relationships between the rock or soil and the fluids (groundwater, soil gas, oil) within them. The engineer must understand the nature of each to identify the appropriate constitutive law. Complications arise due to the heterogeneity of geological materials, e.g., bedding and schistosity cause scale and orientation dependencies of the geological materials.
Numerical modeling of complex geotechnical structures	Such models must accommodate complex constitutive laws and the large spatial variability of the critical parameters in geological materials.
Size of the ground model and boundary conditions	Each geotechnical model requires that the boundaries be fully defined between the part of the ground affected by the engineering structure ('near field') and those parts unaffected by it ('far field') where the natural geological conditions prevail. This will require liaison between the engineer and engineering geologist so that the size of the ground model and the nature of the boundaries are well defined in terms of geomechanical and hydraulic properties and geological variability.
Uncertainty	Because of the above, uncertainties will always exist in geotechnical and geoenvironmental projects. Engineers cope with these uncertainties by specially adjusted design, construction and contractual procedures, such as the "observational method" that involves the collection of both observation and performance monitoring data during construction to allow the implementation of pre-conceived geotechnical design alternatives. Thus, the design process continues throughout the construction period because the properties of the site are uncertain within bounds.

4 A PROPOSAL FOR TEACHING THE APPLIED EARTH SCIENCES TO GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERS

We have identified some geotechnical issues that require the assistance of engineering geologists and hydrogeologists in geotechnical project management, in particular, these require the complexity of both geological phenomena and groundwater conditions to be correctly defined at the site scale. Table 1 identifies the professional competencies of geotechnical engineers as defined by the Joint European Working Group of the International Association of Engineering Geologists (Bock et al., 2004). This competency profile exposes where the applied earth sciences can contribute to successful geotechnical project management.

To teach the applied earth sciences to civil engineering students in a manner that is tacitly accepted as relevant requires some measure of maturity in the student that has been acquired through extensive study and some limited experience. It is for this reason that I propose that the education of geotechnical and geoenvironmental engineers in the applied earth sciences should be delayed until the final year of an undergraduate education or the first year of graduate education.

This proposal seems somewhat utopian given the collapse of interest in teaching the applied earth sciences to undergraduates in geotechnical and geoenvironmental engineering programmes. However, if one considers the intention of the American Society of Civil Engineers (2009) to institute a requirement that between the years 2020 and 2025 it will be necessary for civil engineering graduates to have completed a Master of Science degree (or its coursework equivalent of 30 credits) before writing the professional engineering exams, then there is scope to have geotechnical and geoenvironmental engineers learn the applied earth sciences as more mature students capable of a deeper appreciation of uncertainties and with the aid of better developed reasoning skills.

Goodman (1993) addressed this point in the Preface to his textbook *Engineering Geology: Rock in Engineering Construction*: "*No doubt, mastering advanced engineering mathematics or thermodynamics is "harder" for some students than understanding the principles of engineering geology. But in the practice of engineering, geology may prove to be the harder subject. The penalties for geologic mistakes can be severe, whereas the confidence that comes from having made the right choice cannot be obtained from a formula or theory. In my experience, most engineering students are more at home with formulas and analysis than with colors and grades of truth."*

Such a delay would also mean that these engineering graduate students would come to the applied earth sciences having taken courses in soil and fluid mechanics as well as the calculus and mechanics of materials. Such a background would allow Terzaghi's proposal of a two-semester course to be realized if the professorial teachers were available to teach it.

5 SUMMARY

The increasing specialization of civil engineering has squeezed most if not all geological education out of the curriculum of the undergraduate CE degree in most US universities and many in Canada. This indifference to what Terzaghi and Legget thought to be the essential elements of an undergraduate civil engineering education is profoundly disturbing to those in the applied earth sciences who are in practice with geotechnical and geoenvironmental engineers.

The teaching of engineering geology to all civil engineers as envisaged by Legget and Terzaghi is impossible given the changes that have occurred within civil engineering education since Terzaghi's death. However, the current reorganization of civil engineering teaching that is implied by the American Society of Civil Engineering's Policy Statement 465 (ASCE, 2009), indicates that there is the possibility that the applied earth sciences can be taught at a more advantageous time in the education of those civil engineers planning to specialize in geotechnical and geoenvironmental engineering than was earlier the case. Conceivably this could be the final year of undergraduate education, although it might be preferable for it to be delayed until the first year of graduate study for the M.Sc. degree with specialization in geotechnical and geoenvironmental engineering.

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