INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Shaking the Foundations of Geo-engineering Education – McCabe, Pantazidou & Phillips (eds)
© 2012 Taylor & Francis Group, London, ISBN 978-0-415-62127-4

Teaching the importance of engineering geology using case histories

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ABSTRACT: Geotechnical case histories have been traditionally published in geotechnical conferences and journals as a way to share knowledge and experiences between academics and practitioners. This paper presents our recent experience with the use of failure case histories in graduate coursework as a teaching tool to make students develop an intrinsic understanding and recognition of the importance of geology in civil engineering, and to motivate students into the subject of Engineering Geology. Two tunnelling case histories with a deficient initial characterization of geology are discussed: one involving a tunnel failure in an urban environment, and another one involving extremely difficult tunnelling conditions that produced huge time and cost overruns. Our experience shows that case histories are an effective tool for effective teaching and learning in civil engineering curricula.

1 INTRODUCTION

Geology and engineering geology are important aspects of civil engineering design and construction. In that sense, for instance, Burland (2007) states that the most important decisions in a construction project are always founded on a good geological profile, and that most errors originate from a deficient knowledge of the characteristics of the ground. Unfortunately, however, it is common that not enough attention is paid to the importance of geology in engineering curricula. For instance, students are often only concerned with 'the parameter' (i.e., 'the number') that they need for their computational or analytical model, and it is common that there is not an adequate consideration of the specific characteristics of the soil or rock where the project is located. This is illustrated in Figure 1, where different areas of 'expertise' for students and practitioners with different training are shown.

Such 'lack of interest' for geology not only happens among civil engineering students who, in Peck's words, are unfortunately "led to believe that theory and laboratory testing constitute the whole of soil mechanics" (DiBiagio and Flaate, 2000) but also in practice, as in "too many cases in the past geology has been neglected" (Legget, 1979). For that reason, we believe that geotechnical teachers have an important challenge to demonstrate to their students the importance of engineering geology for the success of a specific project. The aim should be teaching methodologies that *motivate* the student in relation to the importance of geology in civil engineering. Ideally, we would aim to develop "intrinsic" motivation or, in Newstead and Hoskins (2003) terminology, motivation for "personal development", since we feel that such type of motivation is more likely to remain with time during their career.

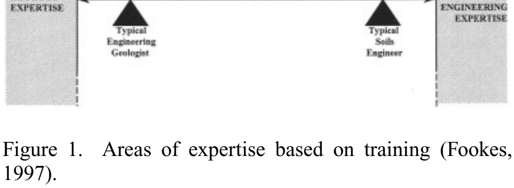

Figure 1. Areas of expertise based on training (Fookes, 1997).

We study the use of geotechnical engineering *case histories* in graduate coursework to develop such intrinsic understanding and recognition of the importance of engineering geology. Case histories can "make a rich learning experience" (Beaty, 2003) and they are, of course, often used in teaching as 'informal' discussion or examples, or as an introduction to a new topic. However, despite the inclusion of specific coursework into some geotechnical programs (see e.g., the "Case Histories in Geology Engineering" coursework in the MSc program at Imperial College London), their use as a "systematic" teaching methodology, from "identifiable needs" such as the appreciation of the importance of geology to "predictable outcomes", and with a planning sequence that incorporates a feedback loop (D'Andrea, 2003) is probably not so common in civil engineering programs.

For that reason, case histories and case studies can be employed to increase the student's 'experience toolbox'. Such case histories should not be limited to a simple problem statement, but they should incorporate deeper geotechnical aspects such as the analysis of the origin of the geotechnical problems, their evolution during construction and, if available, the adopted solutions. Access to such information is made easier by the involvement of the teacher in the project. In that case, one of the objectives of the lectures would be to "transfer" the teacher's own experience (Isaac, 1982). This is in agreement with Bonifazi (2003), who also indicates that study programs should include time for presentation of selected cases, specially those in which the teacher has participated.

Despite the primary interest of case histories in which the teacher has had a close involvement, however, there are situations (due, for instance, to lack of experience in young lecturers or to the specific interest of a project that is well presented in the literature) in which it is advisable to resort to published case histories. Case histories have been traditionally presented in congresses, conferences, and professional meetings such as, for instance, the *International Conference on Case Histories in Geotechnical Engineering* Series. Geotechnical journals also publish case histories on a routine basis, and an international journal entirely devoted to case histories has been recently launched (see the *International Journal of Geoengineering Case Histories* at http://casehistories.geoengineer.org).

In this paper we present our experience with the use of case histories to illustrate the importance of geology for civil engineering and, in particular, for tunnelling projects. More specifically, we present our experiences with the use of case histories as a teaching tool in a 3 ECTS module entitled "Reliability of geotechnical designs" in the MSc program of "Structures, Foundations, and Materials" at the Technical University of Madrid (UPM). The aim is to make students realize that engineering geology is crucial for the identification of failure modes in reliability analyses so that, no matter how advanced or sophisticated our calculation models are, "… if at the very start the geological structure of the site is misinterpreted, then any subsequent […] calculation may be so much labor in vain" (Glossop, 1968).

As we will show, case histories represent a viable approach for teaching and learning the importance of engineering geology. We start with a brief description of the importance of case histories in common geotechnical practice, and we continue with a discussion of two case histories in which geology had an important influence on tunnel behaviour and that were employed in the coursework mentioned above. Finally, the learning outcomes achieved and the results of a survey conducted among the students are discussed.

2 CASE HISTORIES AND ENGINEERING JUDGEMENT

As indicated by Burland (1987), geotechnical materials are completely different to those employed in other fields of civil engineering. For instance, concrete or steel are *manufactured* and *designed* with production specifications and property requirements. On the contrary, Terzaghi (as quoted by Goodman (1999)), warned us that "soils are made by nature and not by man, and the products of nature are always complex", and that "natural soil is never uniform", with its properties changing "from point to point while our knowledge of its properties are limited to those few spots at which the samples have been collected". Furthermore, this has consequences on our computed results, since "in soil mechanics the accuracy of computed results never exceeds that of a crude estimate, and the principal function of theory consists in teaching us what and how to observe in the field".

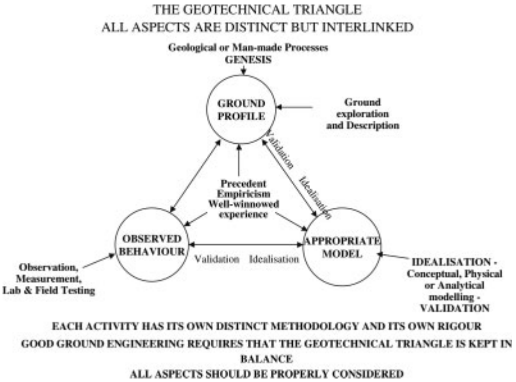

Figure 2. The geotechnical triangle (Burland, 2007).

The discussion above emphasizes the importance of geological and geotechnical investigations, with the objective of defining, *for that specific project*, what materials are going to be found, what are their inherent properties, and how they are going to respond in that particular case. Obtaining such information, however, is not always feasible, and the geotechnical design has to rely to some extent on *experience* and *engineering judgement*, so that, as stated by Peck "the successful practice of engineering requires a high degree of engineering judgement" (see DiBiagio and Flaate, 2000).

One further example of the importance of experience in geotechnical practice is illustrated by Burland's "Geotechnical Triangle" (Burland, 2007). As shown in Figure 2, there are three crucial aspects that need to be considered *in a balanced manner* for a good geotechnical design: the "Ground Profile"; the "Observed behaviour"; and an "Appropriate model". Note that *experience* plays a crucial role in the design process—'in the center' of the triangle—, so that judgment should be based on "precedent empiricism" and "well-winnowed experience".

We must note, however, that such experience and engineering judgement are not inherent to humans (i.e., we are not born with them); therefore, *we need to develop them*. One way is, of course, by 'passive' learning during our professional practice. Unfortunately, "one engineer in one lifetime can hardly be exposed to enough experience to develop all the judgment needed" (Peck, 2004). In addition, in relation to case histories related to 'failures', it is always a good idea to *learn with the mistakes of others*.

For those reasons, we can also use case histories to help develop engineering judgment during a student's education, so that the paradigm of teaching and learning 'from experience' from case histories and case records appears as a viable method for undergraduate and, perhaps more importantly, for graduate teaching. In fact, this approach has been previously employed in the classroom and discussed in meetings of Teachers of geotechnical subjects (see e.g., the work of Lings discussed in the MTGS meeting series as reported in http://www.dur.ac.uk/d.g.toll/mtgs/mtgs91.html.)

3 DESCRIPTION OF THE COURSE

The case histories presented in this work have been employed as a teaching tool in an 'optative' graduate course, entitled "Reliability of geotechnical designs" (offered at UPM) Because it is an 'optative' subject, the number of students is usually small; in previous years it has ranged between 6 and 15 students.

The course has a total amount of 3 ECTS. The instructor's presentations related to the case histories discussed herein take a total of approximately 1,5 contact hours. Students are further requested to work independently on the Yacambú-Quíbor case history (see below), to review the paper and to write a short essay with a summary and with their personal opinions and thoughts about it. This is estimated to take, approximately, an additional 4 hours of the student's time. Furthermore, in this course, the case histories discussed herein also serve as an 'example' from which students can build to broaden the scope of discussion. In particular, students are asked to work independently to prepare and deliver a short presentation (of approximately 10–15 minutes) in relation to other geotechnical 'failure' case histories, where the term 'failure' is employed in a broad sense, to indicate "cases in which performance was not 'as expected' during design".

As general objectives of the "Geotechnical Reliability" course, we have: (i) to familiarize the student with the important aspects of geological and geotechnical characterization under conditions of uncertainty; (ii) to quantify the effects of such uncertainty on the 'success' of geotechnical designs (i.e., failure probability); (iii) to calibrate geotechnical models and parameters given performance observations in a context of uncertainty; and (iv) to incorporate such uncertain inputs and observations into decision making and risk analyses.

4 LEARNING THE IMPORTANCE OF GEOLOGY THROUGH CASE HISTORIES

4.1 *El Carmel tunnel*

(a) Initial collapse

(b) Surface collapse

Figure 3. El Carmel tunnel collapse.

El Carmel tunnel collapse in Barcelona occurred in early 2005, and had huge economical and political consequences. The collapse started as a relatively small sized failure that, despite efforts for stabilization, progressed upwards destroying and heavily damaging some buildings at the surface. Figure 3(a) shows a photograph from the inside of the tunnel taken shortly after the initial failure; and Figure 3(b) illustrates the consequences of the collapse on the surface.

The tunnel had a cross section of (approx.) 100 m^2 and was being constructed with the NATM tunnelling method in a Carboniferous sandstone and micro-conglomerate formation that was overlaid by (unconformable) Quaternary materials and anthropic fills. Its alignment was quasi-parallel to one closeby station that, despite its significantly larger cross section, had been previously constructed without non-standard difficulties. The auxiliary tunnel was mainly designed using geological information related to the design and construction of the station and, unfortunately, very limited geological information about the new auxiliary tunnel location was available.

After the collapse, a forensic team with members from the Technical Universities of Madrid and Catalonia (UPM and UPC) was set up to investigate the causes of the collapse. (The first author was involved in the work of the UPM team.) The details of the analysis, that included geological and geotechnical investigations (boreholes, geophysics, an exploration

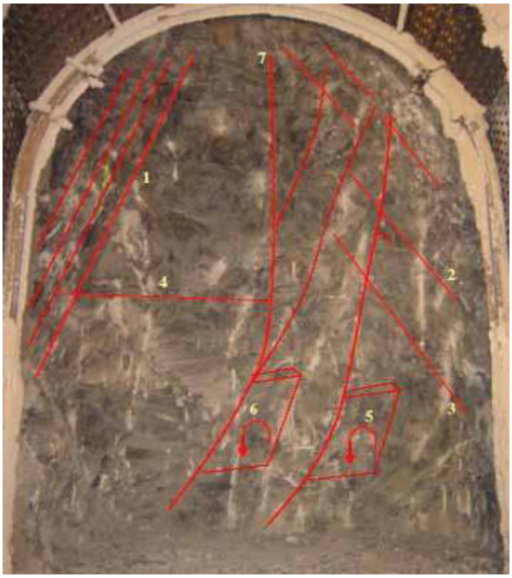

Figure 4. Aspect of the fault zone as observed in the exploratory adit.

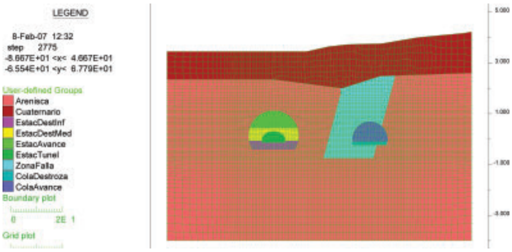

Figure 5. Representative cross section at the location of failure (Jimenez et al., 2008).

adit, in-situ and laboratory tests, etc.), will be presented elsewhere but, in summary, the conclusions were that (in addition to other construction and organizational factors) the presence of *an unanticipated fault zone was the main cause for the collapse*. Figure 4 shows a photograph of the fault zone as intersected by the exploratory adit; whereas Figure 5 shows a cross-section (representative of the position where the collapse started) of the FLAC model developed for the numerical analysis and that illustrates the positions of the auxiliary tunnel, of the tube station, and of the fault-zone.

4.2 *Yacambú-Quíbor tunnel*

The Yacambú-Quíbor tunnel in Venezuela illustrates how a case history from the literature can be employed to emphasize the importance of geology in underground constructions. It is a 23.3 km long hydraulic tunnel with (approx.) 4 m average internal diameter and a rock cover of up to 1270 m that has been considered by many as "the most difficult tunnel in the world" (Hoek, 2001). The tunnel has been recently completed after 32 years (Hoek and Guevara, 2009).

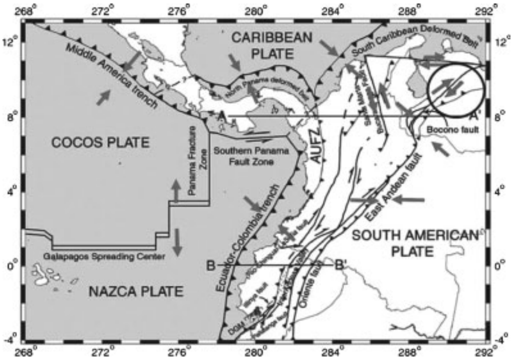

Figure 6. Tectonic regime in the NW South America and Panama. (After Trenon (2002) and Diederichs (2008) and as presented by Hoek and Guevara (2009)). NOTE: The project region appears in a circle in the upper-right corner.

Hoek and Guevara (2009) further discussed the history of the project and the relationship of some of the geotechnical difficulties to unanticipated rock conditions due to a poor understanding of the geology of the area. The discussion below is mainly based on this reference although there were, of course, other non-technical problems (financial, contractual, political) that are not discussed herein. As described by Hoek and Guevara (2009) (see Fig. 6) this area is "one of the most tectonically complex" regions on Earth. In the project region "strike-slip and transpressional faults react to accommodate the mismatch in movement of the surrounding plates" so that, as a consequence, the properties of the phyllitic rock mass range from "strong and reasonably massive" (in the dam area that was the main source of information during site characterization; see below) to "severely tectonically deformed graphitic phyllite" (in which most of the tunnel excavation took place).

The initial characterization of the rock mass was mainly based on the observations during walk-over surveys, exploration adits and a very limited amount of core drilling. In addition, most of the investigations were carried out near Yacambú dam site (at one extreme of the tunnel), where the silicified phyllite rock mass was of relatively good quality. Therefore, the TBM machines were designed for such rock of reasonable quality, although a large percentage of the tunnel length had to be excavated in a much weaker graphitic phyllite where significant squeezing problems were encountered in several other locations (Hoek, 2001). (Figure 7 shows an example of large convergences at the tunnel during repair works in 2006.) As in the case before, it seems clear that an incomplete characterization of the geology lead to unanticipated conditions that were, in addition to lack of knowledge that existed at the time to deal with such heavy squeezing, the reason behind the problems described.

Figure 7. Large convergences at Yacambú-Quíbor tunnel. (Courtesy of Ing. V. Camejo.)

5 OUTCOMES ACHIEVED

To analyze the effectiveness of the case history approach presented herein on the students' learning process, the evolution of students' opinions were studied by means of surveys conducted at the classroom. In such surveys, students were asked about the level of "importance" (in a numerical scale from 0 to 10) that they granted to several aspects related to tunnel design and construction. The specific questions of the survey were related to the following aspects: (i) *Geological* characterization (faults, stress state, etc.) (ii) *Geotechnical* characterization (cohesion, friction angle, deformability, etc.) (iii) construction method (TBM, NATM, etc.) (iv) personnel's experience and quality of construction; and (v) computational models and tools.

Surveys were conducted to find the students' opinions both *before* and *after* the coursework, which allowed us to identify changes of the students' perceived importance in relation to different aspects. In that sense, for instance, student surveys showed that these case-histories had contributed to their appreciation of the importance of geology in civil engineering so that "geological characterization" passed from being considered among the "most important" aspects of tunnelling for roughly 45% of the students before the coursework to approximately 90% of the students after the case histories coursework was completed.

As specific learning outcomes that could be linked to working with these case histories, after a motivated student completes this coursework, he/she would be able to *recall* two important cases of tunnelling in difficult ground conditions and to to *define* sources of geological uncertainties in geotechnical engineering ("knowledge"-related learning outcomes); and, in addition, will *recognize* (and appreciate) the importance of engineering geology for risk analysis and risk mitigation in the context of civil engineering ("comprehension"-related); and to *demonstrate* and *illustrate* several likely failure modes in geotechnical designs ("application"-related).

Note, however, that these outcomes are at the bottom of Bloom's hierarchical level (Bloom et al., 1956), hence indicating relatively low complexity and demand outcomes or a "surface" approach to learning (D'Andrea, 2003). Note however, that they go beyond confirming what is already known about case histories (i.e., that the provide "knowledge"-related outcomes, with students 'remembering' and 'liking' case history information), as we have additional outcomes related to a deeper appreciation of the importance of engineering geology for safe and successful engineering practice ("comprehension" and "application"-related outcomes).

In addition, and although we have not yet implemented this in our course, we argue that when case histories are sufficient in number —hence suggesting a wider 'experience'—, and when they are 'founded' on a good understanding of the underlying mechanisms (see below), the could also help develop 'higher' learning outcomes, such as "analysis"-related outcomes (e.g., to *distinguish* a 'flawed' site characterization program) "synthesis"-related outcomes (e.g., to *propose* a new site-characterization or modification for its improvement); or "evaluation"-related outcomes (e.g., to *criticize* the adequacy of numerical results or to *assess* the geological risk associated to lack of knowledge). A good approach for this would be to ask the students to complete a set of exercises and tasks that are related to the case history (Beaty, 2003) although, in such case, we should make a deliberate effort to make the case study a more substantial part of the course (Pantazidou, 2012). These activities constitute work in progress for us and the results will be presented elsewhere.

6 CONCLUDING REMARKS

We present our experience with the use of case histories to illustrate the importance of engineering geology to geotechnical graduate students. The main objective is to emphasize that a good geological characterization is crucial for the success of civil engineering projects and, in particular, for tunnelling projects; and also to illustrate that the identification of geotechnical failure modes is crucial for risk analysis and mitigation. To that end, we presented the case of an urban tunnel failure in Spain in which an unpredicted fault zone was the main cause for the occurred failure, and we also use an example case from the literature of a tunnel (the Yacambú-Quíbor tunnel in Venezuela) in which extreme difficulties were encountered due to an insufficient geological characterization. Furthermore, the case histories approach is employed as a basis for additional coursework in which the students are asked to prepare similar studies of geotechnical 'failures'.

As an additional note, we argue that case histories cannot be considered to be 'the solution' to all learning needs. One reason is that only low-level learning outcomes (in terms of Bloom's taxonomy) can be obtained unless a significant portion of the course is devoted to such case histories. In addition, case studies employed need to be relevant, as "experience does not always lead to learning" since reflection is a key aspect of learning through experience (Beaty, 2003), and experience (i.e., case histories) needs to be 'founded' on a good theoretical framework for understanding of the underlying mechanics. As Terzaghi warned, "no conclusion by analogy can be considered valid unless all the vital factors involved in the cases subject to comparison are practically identical", so that [some] "engineers who are proud of their experience do not even suspect the conditions required for the validity of their mental operations" and, as a consequence, "practical experience can be very misleading unless it combines with it a fairly accurate conception of the mechanics of the phenomena under consideration" (Goodman, 1999).

Finally, we believe that this case-history approach incorporates other positive aspects that are related to problem-based learning (Overton, 2003) such as, for instance, an increase in motivation of students, and an encouragement of independent learning.

ACKNOWLEDGEMENTS

Ing. Víctor Camejo (Civil Engineer; Venezuela) kindly provided the photograph shown in Fig. 7.

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