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Bridging Geotechnical Engineering Education and Research on Education

Marina Pantazidou
National Technical University of Athens, Greece, mpanta@central.ntua.gr

SUMMARY: This paper is about the use of tools and results from research on education in geotechnical engineering education. The incentive for doing this is to go past the level of individual faculty each improving their own courses to producing educational gains as a community. The literature of discipline-based education research (DBER) provides guidance and examples of how other disciplines, mainly from the sciences, have started this kind of work. Pedagogical content knowledge is a concept also from the education literature that reminds us that as teachers we need to consider content from a combined teaching and learning point of view, which can serve as a useful framework for the collective undertaking to enrich geotechnical engineering education. An important component of pedagogical content knowledge is how students perceive key topics and can be obtained by asking them suitable probing questions. Such knowledge of geotechnical engineering can be articulated, recorded and shared. The paper considers three geotechnical engineering topics, soil classification, shear strength and bearing capacity, from the teaching and learning points of view. Through examples, proposals are sketched for systematic study of student perceptions and the development of targeted educational material. Among the three topics discussed, shear strength emerges as a priority focus.

KEYWORDS: Geotechnical Engineering Teaching and Learning, Discipline-based Education Research, Pedagogical Content Knowledge

1 INTRODUCTION

The gap between findings of research on Engineering Education and teaching practice has been confirmed with surveys of engineering faculty (Borrego et al. 2010) and identified as a barrier to implementing engineering education innovations with impact by the American Society for Engineering Education, which characteristically says (Jamieson and Lohmann 2012):

> "… the dominant approach is based largely on faculty intuition drawn from experiences as students and teachers. Seldom are engineering education innovations grounded in relevant learning theories and pedagogical practices."

One reason for this gap is that engineering instructors cannot see the applied relevance of research on Engineering Education to their own teaching. This perceived irrelevance is not surprising even when the focus is on instruction: a significant number of research findings are about instructional methods, such as collaborative learning or problem-based learning (e.g. Prince 2004), that in principle concern all faculty but in practice no one in particular. If, instead, engineering education research focused on specific disciplines within engineering domains (e.g. Geotechnical Engineering within Civil Engineering), the perception of irrelevance would disappear for at least the instructors of that discipline. But then, targeting a small student and instructor audience would make selection of these research projects doubly limiting for education researchers. Not only funding options will be scarce, but also, unlike the commonly studied science topics at high-school level, most engineering education researchers will not be able to handle such projects on their own: the close collaboration with an instructor from the engineering discipline (e.g. Geotechnical Engineering) will become necessary. What is more, a discipline-focused education research project will be even less probable to be pursued, considering that the engineering instructors must be the ones to initiate such a project, as only they know which are the potentially problematic key topics taught in their own engineering discipline.

This position paper is written for an intended audience that includes all geotechnical engineering instructors and aims to achieve two goals. (1) Identify fundamental topics of Geotechnical Engineering that do or may present teaching and learning difficulties and propose suitable teaching aids. (2) Taking into account the existing literature on Education, sketch the kind of research needed in order to uncover topic-specific learning difficulties of students. Its ultimate goal is to increase the odds of such research projects being undertaken, by giving examples of how elements of the needed research can be embedded in everyday instruction.

2 LITERATURE BACKGROUND

2.1 Discipline-based Education Research

Discipline-based education research (DBER) is the subset of education research that aims to understand and improve the learning of specific topics within a particular discipline. As already alluded to, subjects researched are those taught to large student audiences: mainly at secondary education level, but also introductory subjects taught at engineering schools (NRC 2012). Geotechnical Engineering belongs in the category of specialized civil engineering subjects. Hence, the geotechnical engineering instructor will not find any ready-made result in the DBER literature, but can learn from the research questions asked and the methods employed to answer them. A common, because it is fundamental, research objective within DBER is identifying and recording the relevant prior knowledge (preconceptions) students bring to topics they study, as well as the conceptions they construct for those topics; either the prior or the newly constructed knowledge may contain misconceptions. In other words, discipline-based education research offers instructors the opportunity to view a topic from the vantage points of the learners, which is a prerequisite for understanding why some students ‘don’t get it’.

Discipline-based education research rests on two fundamental precepts: (1) there is no one-to-one relationship between content and content learned and (2) instructors will benefit from knowing all the possible relationships. Fortunately, the systematic study of students’ conceptions reveals that these can be grouped in a limited number of categories (Bowden and Marton 1998).

To broaden the discussion on teaching and learning of specific topics, let’s call ‘A’ a fundamental concept of a discipline appearing in its textbooks. ‘B’ is how instructors think of this topic and convey it to their students and ‘C’ is this same concept in the minds of the students, as shown in Figure 1. In the sciences but also in engineering, it is commonly assumed that, to a large extent, ‘A’=‘B’. This is not necessarily so. Not due to flawed textbooks or incompetent instructors, but because ‘A’ is not a single occurrence, but an envelope of occurrences. It is like the difference between the target dead center and a halo around the center. Within this halo, more than one alternative ‘B’s’ exist (see examples in Section 3.2). Engineering instructors may elect to present a topic as a single occurrence (dead center), thus postponing the need to address the confusion of dealing with the halo until students graduate. Whether instructors present ‘A’ as a point or an envelope, ‘C’s’ will lie within or outside the commonly accepted envelope. In the latter case, instructors typically perceive that students ‘have it wrong’ or, to use an engineering term, a failure in understanding.

After uncovering the different types of failure, i.e. the different types of incomplete or erroneous understanding (e.g. Prince et al. 2012), discipline-based education research creates (e.g. Pantazidou 2009) and evaluates targeted remedial interventions (e.g. Slotta and Chi 2006). The research on how students understand fundamental science and engineering topics is voluminous (NRC 2012). This type of research has focused on the 'A'-'C' relationships, and mostly for science topics where 'A' has a narrow envelope and, hence, for teaching purposes, it can be assumed that 'A' and 'B' coincide. Clearly, evidence of differences between 'A' and 'C' is a more comfortable finding for instructors, when compared to differences between 'A' and 'B'. The author is not aware of research studies comparing 'A' with 'B's': such research requires high-level disciplinary expertise so, understandably, is a rarity. However, that there exist varieties of 'B' makes sense, considering that the versions of the pedagogical content knowledge of each individual instructor cannot all be identical.

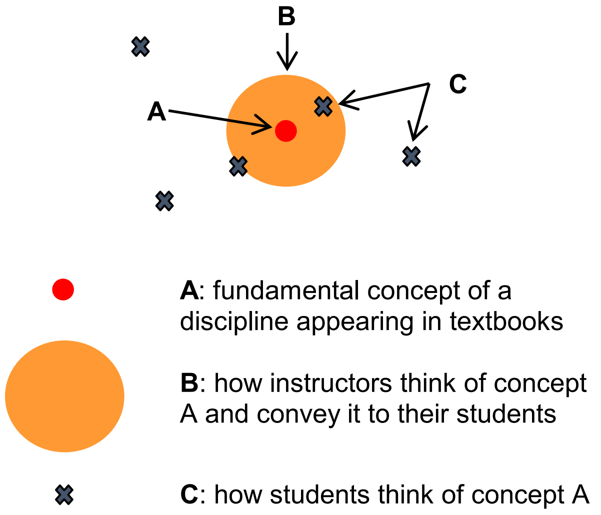

Figure 1. Schematic representation of varieties of content: **A**: a fundamental topic in a discipline, **B**: how instructors and **C**: how students think of this topic.

2.2 Pedagogical Content Knowledge

Pedagogical content knowledge is a concept introduced in the education literature by Shulman (1986) to refer specifically to the knowledge from a teaching point of view for specific topics within a discipline. Pedagogical content knowledge is one of the three components of the content knowledge of the instructor in the domain; the other two components are subject matter content knowledge and curricular knowledge (i.e. of available educational material). Figure 2 stresses the distinction between *subject matter* content knowledge (e.g. of a geotechnical engineering researcher or practitioner) and *pedagogical* content knowledge (e.g. of a geotechnical engineering instructor), as well as between pedagogical content knowledge (which is domain-specific) and pedagogical knowledge of teaching (which is domain-general, e.g. it includes generic teaching tips).

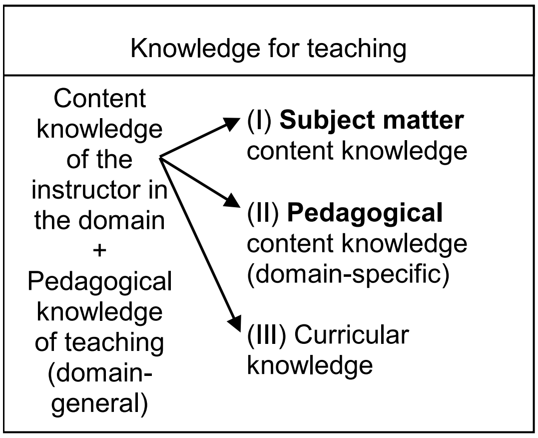

Figure 2. Distinguishing different types of knowledge for teaching: pedagogical content knowledge is one component of the content knowledge of an instructor in the domain.

Shulman (1986) summarized the ingredients of pedagogical content knowledge as "knowledge of the ways of representing and formulating the subject that make it comprehensible to others" and included, for the most regularly taught topics in a subject area, "the most powerful analogies, illustrations, examples, explanations and demonstrations". In the absence of a concerted effort of a discipline to gather and disseminate the better samples of this pedagogical knowledge within the discipline itself, it makes sense that there exist varieties of 'B' (Fig. 1). Shulman (1986) also included in this knowledge "an understanding of what makes the learning of specific topics easy or difficult", and stressed the prevalence of student misconceptions. Misconceptions may concern either meanings constructed while learning a subject, or purposes for the subject being taught. Instructors will be most effective in helping their students if they know a priori the misconceptions that students either bring to a topic or incorporate in new understandings. Recently, Sadler et al. (2013) provided evidence supporting such assertions; specifically, they identified positive correlations between higher familiarity of instructors with the misconceptions in the subjects they teach and better performance of their students.

Some of these misconceptions eventually become known to instructors with years of experience, provided that they have a habit of systematically probing their students. However, a teaching lifetime will likely not be enough for instructors to uncover by themselves this knowledge for all the topics they teach. Probing students' conceptual understanding is a time-consuming undertaking that presupposes one-on-one time, and requires experience in asking suitable questions; without skillfully crafted questions, acquiring this knowledge hinges on the metacognitive self-awareness and communication skills of students.

Bowden and Marton (1998) discuss a number of studies that have developed qualitative questions to diagnose preconceptions and misconceptions, monitor understanding and assess impact of instruction. In fact, Bowden and Marton (1998) consider formulating suitable qualitative questions as the key undertaking in finding out what is learned by students. To this end, they offer the following guidelines. The questions have to be open to different perspectives so that students decide on their own the relevant aspects of the problem that need to be addressed. They should preferably be stated without using standard technical jargon, because "specific facts and procedures usually rest on taken-for-granted ways of seeing, which are not put to the test". Finally, these questions should focus on fundamental concepts in the field that are central in the development of key skills.

Following the ideas of Bowden and Marton (1998), Pantazidou (2009) formulated the following qualitative question to probe student understanding for the topic of soil structure:

> "In your opinion, in which soil type may we encounter higher porosity, in a sand or a clay? How do you justify your opinion?"

In one group of 5th-year students at the National Technical University of Athens, the majority of students (28 out of 39) answered "sands"; many of them (10 out of 28) justified their answer by erroneously associating the larger pore size of sands with higher pore volume and, hence, higher porosity. Note that this type of question offers students more latitude to decide on their own how to answer it compared with a related factual question that would essentially ask them to check information given in textbooks. For example, a question such as:

> "What is the range of porosity values for clays and sands?"

does not offer students opportunities to think why the upper limit of porosity for clays is higher than that for sands. Open-ended qualitative questions are not only research tools; they can serve equally well as regular assessment questions that can be incorporated in lecturing, assignments and quizzes (Pantazidou 2009) and often serve as mirrors that reveal to the students themselves how they have organized knowledge.

Unfortunately, assessment in engineering courses is based primarily on problem solving and analysis. Rarely does assessment investigate the nature of concepts formed by students or how do students synthesize related mental constructs and concepts. Tellingly, Montfort et al. (2009) found no significant improvements in conceptual understanding of key mechanics concepts among students in early and late years of an undergraduate civil and environmental engineering curriculum, as well as at the graduate level, despite improvements in their computational skills.

A clarifying comment may be in order concerning eliciting misconceptions from students in a classroom setting. Students should not be penalized for giving a wrong answer, but graded for their effort to explain their thought process. Uncovering students' misconceptions does not constitute an implicit attempt to have students fail. It is a necessary first step that acknowledges students' conceptions, which can then guide interventions to change inaccurate mental models.

The ultimate goal of the paper can now be written more specifically as follows: (i) to aid in the gathering of the dispersed pedagogical knowledge of Geotechnical Engineering that resides in the literature and the minds of individual instructors, (ii) to motivate geotechnical engineering instructors to contribute to the creation of this knowledge and (iii) to suggest everyday teaching tools for doing so.

3 TEACHING AND LEARNING OF KEY GEOTECHNICAL ENGINEERING TOPICS

The author has taught for several years introductory courses in Geotechnical Engineering (in some institutions such courses are called Soil Mechanics). Her research area is Environmental Geotechnics, so she had fewer opportunities to ponder, as part of her research, on the concepts involved in the fundamental topics of Geotechnical Engineering compared with geotechnical engineering colleagues with traditional geotechnical engineering research interests. However, empirical evidence from her own teaching experience and that of her instructor colleagues suggests that the overlap of the set of fundamental concepts in introductory engineering courses and each individual instructor's research area is small. Hence, it is probable that pedagogical knowledge of every topic will be beneficial for many instructors. In any case, with a specialty outside the core of traditional Geotechnical Engineering, the author has greater freedom to admit that she has spotted gaps in this knowledge. The sections that follow discuss identified gaps in the recorded pedagogical knowledge of three topics that are included in all geotechnical engineering introductory courses, taking into account how these topics are presented in geotechnical engineering textbooks. The three topics are soil classification, shear strength and bearing capacity.

3.1 Soil Classification

Soil classification is typically taught very early on in an introductory geotechnical engineering course. Likewise, it is one of the first chapters in many geotechnical engineering textbooks, which invariably present one of the most common classification systems, the Unified Soil Classification System (USCS). In subsequent chapters, USCS soil designations reappear vary rarely, if at all, so the textbook reader is left with questions regarding their applied usefulness. The author gets the same impression when reading geotechnical consulting reports. Soils are being classified according to the USCS because this is the information that typically accompanies soil boring logs, but the decision value of this information is not discussed or demonstrated in projects involving soils in their natural state.

The original description of the USCS development (US Army Corps of Engineers 1960) and the fact that classification refers to disturbed samples, guided the author to arrive at the following tentative conclusion: the USCS designations are meaningful mostly when evaluating different soils to be used for the same purpose, a situation relevant to earthworks. This conclusion remains tentative after consulting several geotechnical engineering textbooks (e.g. Briaud 2013, Holtz et al. 2011, Kavvadas 2002, Knappett and Craig 2012, McCarthy 2002): the problems at the end of the soil classification chapter present soil gradation and plasticity data and ask students to classify the soils, but not to evaluate soils on the basis of their USCS designation. One exception was found in the engineering education literature: Fiegel (2013) describes the design of an introductory geotechnical engineering course on the basis of detailed learning objectives for each one of the nine units covered in the course. The soil classification unit includes the objective "Predict the engineering behavior of soils (relative to compressibility, strength, and hydraulic characteristics) based on classification results”. Fiegel (2013) tests whether this objective is met by asking quiz questions such as:

> “You have designed a retaining wall for a client. Your next task is to develop a specification for the backfill to be placed behind the wall. Which soil would you prefer to specify: CL, ML, SP or GC? Why?”
>
> “Which of the following soils would you most like to use as a pavement subgrade material assuming the road is to be constructed in a relatively warm and arid environment: CL, ML, SM, SP or GW? Why?”

The absence of problem questions such as the above from geotechnical engineering textbooks suggests that something that is not assessed is not presented either and likely points to a gap in the collective pedagogical knowledge of Geotechnical Engineering.

When focusing on the soil categories themselves, from the four major types (gravel, sand, silt, clay), silt appears to be the most elusive. Almost all soils textbook problems consider either clay or sand soils. After the soil classification chapter, readers of most textbooks or students in most geotechnical engineering courses are free to forget about silt for the remaining of the book, of the semester or even of their studies. No textbook author seems interested in making problem sets with silts. A rare exception might be a groundwater problem, where a silt will appear to provide a moderate permeability and make the answer look right (not too fast, not too slow flow). Interestingly, the plasticity chart of USCS lacks an area dedicated exclusively to silt; it assigns a tiny area above the A-line to pairs of low plasticity silt and clay, ML and/or CL, and the area below the A-line to pairs of silts and organic soils of low or high plasticity, ML and/or OL, MH and/or OH.

The author spotted gaps in her knowledge of silts when she started asking herself somewhat philosophical questions such as “is there such a thing as pure silt?” or “can we define silt using characteristics of its own, or do we define it mostly in terms of how its behavior differs from that of clay?”. The research literature of Geotechnical Engineering is not particularly helpful in providing insights, considering that there does not exist any well-known ‘eponymous’ silt (in analogy to several ‘eponymous’ clays, e.g. London clay, Boston clay, etc.) or any research group focusing on experimental investigation of a pure silt.

Two pieces of serendipitous information provided for the author some guidance on silt. First, Orr’s (2012) remark that Ireland has no clays, only mixtures of silts and clays. In these situations, it will be of prime interest to determine the contribution of silt to the properties of the silt-clay mixture. Second, the fact that there are no clay soils on the moon (Duncan and Wright 2005): in a world without clays, it would be of practical interest to differentiate between sand and silt. With these two ideas, the following tentative explanatory framework emerges. There are two major categories of soils –granular soils and clays– and there are three categories of granular soils – gravel, sand and silt. Geotechnical engineers care to differentiate silts from clays because a silt might be mistaken for clay, but without the properties of clay, since a silt is more permeable, less plastic and exhibits less creep. Hence, it might perhaps be useful to think of silt as the ‘fool’s gold’ (pyrite) of civil engineers (perhaps in reverse?).

It is suggested that the geotechnical engineering community enunciates its stance on the usefulness of the USCS and similar soil classification systems and on the geotechnical essence of silts. Likewise, it is suggested that textbooks modify their soil classification section and problems in this and subsequent sections to assist both students and instructors with addressing questions about the purpose of teaching those topics.

3.2 Shear Strength

Depending on how early geotechnical engineering instructors present the Mohr-

Coulomb failure criterion in the discussion of shear strength, students may conclude that the Mohr-Coulomb failure criterion is (the essence of) the shear resistance of soils. In addition, depending on what instructors say (or don't say!) about the equation relating shear, τ, to normal stress, σ', $\tau = c' + \sigma' \tan\varphi'$, students may:

− understanding No 1: assign meaning to c' and $\tan\varphi'$, e.g. relate each parameter to the presumed respective mechanism, i.e. cohesion and friction, that contributes to shear resistance, or

− understanding No 2: think of c' and $\tan\varphi'$ as the inclination and intercept of a straight-line approximation of a curved failure envelope that delimits safe τ–σ' combinations, i.e. think of them more neutrally as the 'a' and 'b' parameters of a straight line, $y = b + ax$.

As already mentioned, instructors will not have access to the conceptions students create for the shear strength of soils through number problems asking for analysis of results from triaxial tests, etc. At best, instructors, and the geotechnical engineering community, can infer aspects of problematic conceptions through errors made in analyses, e.g. in the case study of the Nicole Highway collapse, where shear strength was modelled with effective stress parameters, as $\tau/\sigma' = \tan\varphi'$, instead of the undrained strength of the material, S_u. Use of the undrained shear strength in the analyses would have predicted well the observed displacements of the excavation walls. Overestimation of strength, due to the use of effective stress parameters, lead to underestimation of the displacements by a factor of 2 (Simpson 2012: p. 39).

Instead of number problems, instructors should create conceptual qualitative questions-assignments in order to identify the elements students pick from instruction in Mechanics and Geotechnical Engineering to form the concept 'shear strength of soils'. In one such assignment in a course on Slope Stability, the author asks students to locate 2-3 alternative definitions of shear strength primarily from geotechnical engineering textbooks and also from the Internet. The assignment then asks students to explain which definition they prefer and to explain the technical criteria on which they base their answer. Student preferences reveal which components they consider to be essential elements for the concept 'shear strength'. Students often choose definitions that include the Mohr-Coulomb failure criterion, and explain that a good definition should include the "mechanisms" or "properties" (both terms are taken from students' answers) of cohesion and friction, as represented by c' and $\tan\varphi'$. Note that these are graduate students, so the beliefs that c' and $\tan\varphi'$ stand for something fundamental in the behavior of soils is not superficial but rather entrenched. These findings suggest that simplified expositions of concepts in introductory courses, e.g. "use $c'=0$, $\tan\varphi'$ for sands and $c'\neq0$, $\tan\varphi'$ for clays", may lead to persistent misconceptions that will be difficult to uproot in later courses.

Students' misconceptions can partly be caused or further reinforced by the choice of terms. The terms often used for c' and $\tan\varphi'$ contribute to understanding No 1, as also remarked by Burland (2012a, b), who uses the terms 'effective cohesion' and 'effective angle of shearing resistance'. Specifically, Burland (2012b: p. 177) comments that he:

> "prefers the term 'effective angle of shearing resistance' [for φ'] as its value depends on other (more dominant) factors than inter-particle friction, such as particle shape and grading."

The author further believes that the term 'cohesion intercept' (e.g. Mesri and Abdel-Ghaffar 1993) is an improvement over 'effective cohesion'. In her teaching, she uses the term 'shear strength parameters' for both c' and φ', in order to reinforce understanding No 2. It is important to stress that if students arrive at understanding No 1, this does not necessarily mean that the instructor intended this outcome. Independently of the instructor's intentions, students may envision a frictional component of shear resistance, exhibited by all soils –but somehow missing in undrained conditions– and manifested through φ', and some mechanism that holds clays together, which is called cohesion and is manifested through c΄. This nebulous entity, cohesion, is especially troublesome, since a clear definition of it is missing from the contemporary geotechnical literature (see Section 3.2.1).

Now consider starting instruction on shear strength by focusing on what happens at the particle level: students may tend less to cling onto simplified mechanisms of cohesion and friction and be able to develop generative mental models, at least for granular soils. Burland's (2012b) description of what happens during shear at (i) critical state and (ii) residual state is helpful for this particle-level understanding of shear: soils with no/low clay fraction undergo rolling shear at both states, while soils with high clay fraction exhibit turbulent shear at critical state and sliding shear at residual (p. 178-181 and Fig. 17.11, drawn with data from Lupini et al. (1981)). However, for effective teaching that aims to clear up misconceptions, instructors first need videos and particle-tracking tools and then diagrams. The work by Viggiani and coworkers (e.g. Andò et al. 2012) provides examples of research findings that can form the basis for the visuals needed for instruction: the use of X-ray tomography to track individual grains during shear loading provides information on the magnitude of the rotations of individual particles and on the number of contacts between grains, both of which change during shearing.

3.2.1 Shear Strength of Clays

The shear strength of clays is particularly problematic for three reasons. First, it has troubled the minds of great geotechnical engineers in the early decades of the discipline. According to Peck (1985: p. 123), "[Terzaghi] regarded the shearing resistance of clays, which at the time [1925-1927] he simply termed 'cohesion' [quote marks appear in the original], as the product of capillary pressure and the tangent of the effective friction angle. Although conveniently measured as half the unconfined compressive strength, the 'cohesion' of clays was thus no different in principle from the friction of sands." It seems that, out of reverence for Terzaghi, geotechnical engineers have kept the term and also kept searching for an appropriate corresponding concept! Second, most students are left with the impression that all clays have a cohesion intercept. These students cannot handle conceptually the failure envelop of a normally consolidated clay going through the origin of the σ', τ axes, which makes them wonder how did the mechanism of cohesion disappear. Third, students also have difficulty handling conceptually the approach of using a constant value for S_u for the purposes of undrained analysis. The author has asked students –of a graduate course– how do they imagine the undrained condition and got an answer that "the soil changes consistency and becomes like modelling clay". In other words, students, having assigned meaning to each shear strength parameter, believe that, during undrained shear, clay soils somehow turn into materials that resist loading only through cohesion but not through friction.

Luckily, Burland (2012a: p. 156-157) brings some clarity to phenomena and terms by statements such as:

> "There is an unfortunate tendency in practice to refer to 'cohesive' and 'non-cohesive' soils to distinguish between soils of high or low clay content. This can be very misleading, as many normally consolidated soils do not exhibit cohesion [i.e. cohesion intercept], while many granular soils can be bonded. Moreover, all soils that are sheared without allowing drainage exhibit undrained strength which is often treated as an equivalent cohesion in analysis. True cohesion in a soil is a very difficult property to determine and its precise definition is far from clear. It is much better simply to refer to 'clayey soils' and 'granular soils' without implying anything about their cohesion (sometimes the terms 'fine-grained' and 'coarse-grained' are used)."

Although Burland does not attempt a definition of true cohesion, statements from chapters on soils as particulate materials (Burland 2012a) and on strength and deformation behavior of soils (Burland 2012b) suggest that inter-particle bonding and true cohesion are related. Burland (2012a: p. 153) notes that frequently, the contacts between the particles are essentially frictional. However, in many natural soils there is a small amount of bonding between the particles either due to cementation or physicochemical effects. In addition, he stresses that physicochemical bonds can develop over quite a short period of time in clay soils and clarifies that the point of the maximum curvature of an oedometer compression test corresponds to the point when significant particle slip begins to take place, often due to breaking of inter-particle bonds (Burland 2012b: p. 186). Atkinson (2007: p. 136) clarifies that true cohesion can only be examined at zero effective stress, creating practical difficulties for fine-grained soils where any moisture will create suction, raise the effective stress and, hence, the strength. He further stresses that even when soils have true cohesion, at critical state it is usually very small, only a few kiloPascals, which is too small to measure reliably in conventional laboratory tests.

Perhaps one way of helping students distinguish between ‘cohesion intercept’ and ‘true cohesion’ is using Burland’s argument that we would assign to all soils a constant S_u (cohesion intercept), if drainage were not allowed: if instructors showed to students results from UU tests on sands, they could demonstrate that a sand not free to drain behaves like a clay. Another set of tests of potential educational value to students would involve UU and CU tests performed on clay samples practically from the same location. The author believes that until the geotechnical engineering community improves analyses and imaging abilities by orders of magnitude and, thus, becomes able to support the understanding of the shear resistance of clays by showing what is happening at the microscopic level, it will need laboratory experiments designed specifically for educational purposes in order to reinforce concepts and dispel common misconceptions.

3.3 Bearing Capacity

Bearing capacity can be introduced using two approaches, both problematic concerning their theoretical justification. The first is to just present the three-term formula with the N_c, N_q, N_γ factors, and describe –at high level– sources of resistance and the assumed mechanism of failure (e.g. McCarthy 2002: p. 474). The other approach is to start deriving piecemeal each part of the formula, making various calculation maneuvers, and then stitch the parts together. The author is grateful to Salgado (2008: p. 417) for acknowledging that:

> “although it is not theoretically correct to superimpose the effects of c, q_o, and γ, [… the bearing capacity equation] has been used in practice for decades”,

but it would be even better if this statement followed immediately after the presentation of the bearing capacity equation (p. 413), instead of being buried within a section indicated with an asterisk as “containing more challenging material”. Whatever approach instructors take, they then have to talk about the various correction factors for differences in footing shape and depth, shape of shear zone, etc. Lastly, instructors have to add that we apply a factor of safety of three, which, as noted by Atkinson (2007: p. 9), is not a factor of safety in the sense that we guard against uncertainty, but we apply it to limit settlements.

Terzaghi and Peck (1967: p. 218), early on in the bearing capacity section of their classic textbook, state clearly that:

> “No general solution has been found that rigorously satisfies Eq. 16.5 [i.e. the Mohr-Coulomb failure criterion] and also takes into account the weight of the soil, the influence of the depth of surcharge and the real distribution of vertical and horizontal forces on the base of the footing”.

Thirty years later, in the 3rd edition of the same book (Terzaghi et al. 1996: p. 259) the same phrasing is used. But at least, as a teacher without consulting experience in traditional Geotechnical Engineering, the author feels relieved to be able to quote geotechnical engineering giants and start the bearing capacity unit by stating that “you may be disappointed to learn that we don’t have a good analytical solution...” but still uncomfortable having then to add “...but this is the best we can do” (for the last 50+ years). The remaining paragraphs of this section discuss teaching materials that would potentially render the teaching of bearing capacity less awkward.

Considering the assumed shape of the shear zone developing around a footing, it is useful to be able to substantiate this shape with finite element analysis results, of the type produced by Potts and Zdravkovic (2012: p. 43) showing vectors of incremental displacements below a footing. Regarding the shape, most textbooks discuss three modes of failure capacity, i.e. general, local, and punching. However, Salgado (2008: p. 447) questions the need to postulate local and punching failures: it would be good to see results from rigorous analysis replicating (or not) these failure modes.

While the author is not in a position to reconcile the various objections raised against common exposition approaches for bearing capacity, she found illuminating a comment made by Haigh (2012):

> “One of the major benefits from showing real data in comparison to analytical design approaches is, in my view, the question that comes from the data of “what is the bearing capacity?”. The data [for sand] tends to show a continuously increasing load with increasing penetration, giving an effectively infinite capacity if we are willing to accept infinite settlement. The use of a ‘bearing capacity’ in sand is thus implicitly about determining allowable settlement. This was heavily discussed by Prof. Bolton in the 52nd Rankine Lecture, and I believe is a very important educational outcome.”

Indeed this is a very important educational outcome, which will hopefully motivate the geotechnical engineering community to produce suitable data and visuals and make them available to all geotechnical engineering instructors.

Regarding the (un)satisfactory performance of the bearing capacity equation, the geotechnical engineering community should compile the evidence differentiating the cases when the bearing capacity equation produces good results (e.g. Potts and Zdravkovic 2012, Salgado et al. 2013) from those it does not. This is both an important teaching question and a research topic. As a teaching need, it must be addressed with materials prepared specifically for this purpose, in a student-friendly and instructor-friendly manner.

4 CONCLUDING REMARKS

In this position paper the author combined sources from two areas of literature to suggest changes that have the potential to bring about improvements in the teaching and learning of Geotechnical Engineering. The first area of literature includes findings from research on Education and in particular from discipline-based education research. The second area of literature includes geotechnical engineering textbooks and other geotechnical engineering documents providing various syntheses of the field, such as manuals (e.g. Burland et al. 2012) and articles describing the evolution of soil mechanics concepts (e.g. Peck 1985). This second area of literature represents to a significant extent the collective pedagogical knowledge within Geotechnical Engineering. Taking into account the research literature of Education, the author argued for the enrichment of the existing pedagogical knowledge of Geotechnical Engineering, through the development of targeted educational material and through collaborations in education research projects, elements of which can be embedded in everyday instruction.

The author starts from the premise that each engineering discipline needs the kind of engineering education research that will collect, create and disseminate pedagogical knowledge of the specific topics that are most central to the discipline and especially those that present learning difficulties to students. This research has to be carried out in collaboration between education specialists and engineering instructors, who will jointly identify candidate key topics and study how teachers and students perceive these topics. Concerning students, this research has to record relevant preconceptions and misconceptions, which will guide instructional interventions.

As 'yeast' for this kind of research, this paper chose three candidate fundamental topics from Geotechnical Engineering, namely, soil classification, shear strength and bearing capacity, and discussed their teaching and learning aspects. For soil classification, the author identified the need to clarify the applied purpose of soil classification systems and to expose students to problems and projects involving silts. For shear strength, some first steps to identify student conceptions revealed that students mistake shear strength parameters for shear strength mechanisms. The community of geotechnical engineering instructors should pool resources to create qualitative probing questions to be used in class, produce visuals showing what is happening during shearing at the particle level, and perform experiments designed to clarify concepts (e.g. drained – undrained). Shear strength is *the* major consideration in soils; hence, it is a good candidate topic for a full blown research project involving engineering education specialists and geotechnical engineering instructors. Lastly, bearing capacity is a topic that the teaching difficulties it presents point to the need for undertaking projects with combined research and education goals.

The existing body of engineering education research can now provide a framework for rethinking the teaching of fundamental geotechnical engineering topics. It is the author's impression that the geotechnical engineering community, without committing to a consensus on fundamental concepts, has moved on to other research areas. It is hoped that this rethinking will provide motivation for geotechnical engineering researchers to revisit some of the topics that have been gathering some dust for the last couple decades and produce new knowledge that, in turn, will increase pedagogical knowledge for these topics. Shear strength and bearing capacity are excellent candidates for demonstrating with concrete results synergies between research and education.

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