17th International Conference on Soil Mechanics and Geotechnical Engineering, Alexandria, Egypt, October 5–9, 2009

Student understanding of the concept of soil structure guides instructional interventions

La compréhension du concept de la structure du sol de la part des étudiants guide les interventions d' enseignement

M. Pantazidou
National Technical University of Athens, Greece

ABSTRACT
This paper presents a methodology instructors can use in class to elucidate concept understanding in order to design appropriate interventions. The methodology consists of (i) phrasing qualitative questions on fundamental course concepts and (ii) identifying in the answers the main categories that describe the variation of the students' thinking. The application of the methodology is demonstrated for the concept of "soil structure" in an environmental geotechnics course. The results reveal the students' misconceptions related to soil porosity and permeability. To address these misconceptions, alternative in-class activities are discussed.

RÉSUMÉ
Cet article présente une méthodologie que les enseignants peuvent utiliser en classe pour élucider la compréhension de divers concepts afin d'élaborer des interventions appropriées. La méthodologie consiste à (i) formuler des questions qualitatives sur des concepts fondamentaux du cours et à (ii) identifier dans les réponses les catégories principales qui décrivent la variation dans le mode de penser des étudiants. La démonstration faite ici concerne l'application de cette méthodologie au concept "structure du sol" dans un cours de géotechnique environnementale. Les résultats révèlent les idées fausses des étudiants par rapport à la porosité et la perméabilité du sol. Pour remédier à ces idées fausses, on discute ici certaines activités alternatives en classe.

Keywords: geotechnical instruction, soil structure, clays, concept, conceptual knowledge, misconception, conceptual change

1 INTRODUCTION

At some point in their careers instructors invariantly experience bafflement at some of the errors made by students. Most experienced teachers with time develop strategies to minimize the frequency of these errors. Few instructors, however, can enunciate a systematic methodology for determining the misconceptions underlying the errors and, ideally, making suitable instruction modifications. This paper aims at proposing such a methodology and demonstrating how it can be incorporated in regular instruction (i.e. not necessarily in a research project on engineering education).

Instruction, in general, targets two major categories of knowledge: declarative knowledge ("know that") and procedural knowledge ("know how"). Engineering instruction in particular focuses more on procedural knowledge, especially during the later years of an undergraduate engineering curriculum. Conceptual knowledge, on the other hand, can be thought of as a subset of declarative knowledge and refers to the building elements of a domain and their interconnections. These are constructed over time by the learner and used, knowingly or not, to provide some structure to the subject domain. In engineering schools, declarative knowledge is often assessed with theory-related questions (e.g. asking students to perform derivations, or to choose among multiple factual affirmations), whereas procedural knowledge is assessed with problems involving calculations. Few learning experiences and assessment exercises target specifically conceptual knowledge, which is tested indirectly, since it feeds both into declarative and procedural knowledge. This hypothesized relationship is logical, but not well understood nor demonstrated (Streveler et al. 2008). As a result, unless constructing and using specially-phrased diagnostic questions, it will be difficult to attribute recurring errors in problem solutions to either a conceptual or a procedural mix-up.

Asking questions about the building blocks of knowledge, as well as how these are deployed by the learners when faced with a cognitive task, yields a view of the learning process that is closer to the learner's than the teacher's perspective. Building on traditions in Instructional Psychology, Educational Research has developed tools that make possible to obtain answers to the questions just mentioned. One such technique consists of (i) accounting exhaustively for the procedural constituent elements of archetypical problems students confront in a domain and (ii) compiling short multiple-choice questions targeting each of these elements, which, in turn, are underpinned by a relatively small number of concepts. The outcome of the exercise is the collection of the questions, known as concept inventory, which after validation can be used either diagnostically or for assessment. The concept inventory approach was used by Steif (2004) in statics, a fundamental course in civil and mechanical engineering. According to Steif (2004), a representative statics problem is decomposed to (i) parsing of the system, (ii) reasoning about forces connecting parts, (iii) isolating bodies to impose equilibrium conditions and (iv) applying the equilibrium principle to selected bodies. For a common statics problem with blocks and ropes, a typical multiple-choice concept question would address the forces present in the free body diagram of a subset of blocks and cords (Steif and Hansen 2007).

Decomposition techniques such as the one described above are best suited to identify exactly where students make errors (i.e. they do not see that the forces that are equal and of opposite directions are exerted on different bodies), rather than why (a question that will have to unravel the understanding of force). Answering the "why questions" requires a probing of a different kind, offered by an approach known as phenomenography, which seeks to unveil students' mental models of concepts. Among its proponents, Bowden and Marton (1998) discuss a number of studies that have developed qualitative questions to diagnose "pre-conceptions" (what students bring to instruction), monitor understanding and assess impact of instruction. In fact, Bowden and Marton consider formulating suitable qualitative questions as the key undertaking in finding out what is learned by students. Within this tradition falls the work presented in this paper.

2 PROBING PERCEPTIONS OF SOIL STRUCTURE IN THE CONTEXT OF A GEOTECHNICAL CURRICULUM

In selecting topics and phrasing suitable qualitative questions, the guidelines given by Bowden and Marton (1998) become useful. 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.

The benefits resulting from the answers to these questions are manifold. They help the instructor (i) determine the "initial conditions" of the students (in other words, the pre-existing ideas from physics, mechanics and even from direct experience students bring to an engineering course); (ii) become familiar with the less technical language that comes naturally to novices; and (iii) diagnose any misconceptions. The non-technical nature of questions makes them suitable for use both before and after instruction, thus incorporating seamlessly assessment in instruction. In addition, they provide a repertoire of explanations the instructor can re-introduce in the classroom and invite students to critique.

The concept explored herein is soil structure. Soil structure refers to the arrangement of soil particles relative to each other and to what holds them together. By implication, soil structure also refers to the pore space created among the particles.

Soil structure is a generative concept, in the sense that beliefs on pore space characteristics will play a role on predictions of crucial aspects of soil behavior, such as compressibility and permeability. However, since soil mechanics treats soil as a continuous material by practical necessity, students have few opportunities to question their beliefs on soil structure. Hence, not only is soil structure a key concept, but also has many chances to escape unexamined because it is not directly useful for problem solving.

In most civil engineering curricula, students take one or two courses on soil mechanics, where they are introduced to the concepts of soil structure, permeability and compressibility. In the beginning of their first course, students may be introduced to a qualitative description of the geometric arrangement of soil particles and the fundamental differences between sands and clays, the particles of which are held together with gravity forces and electrical forces, respectively. These introductory lectures commonly include a reference to the electrically charged surfaces of clays that attract water. The presence of this water makes clay moldable and solid-looking. The clay-water interaction phenomena and the huge surface area of the tiny, plate-like clay particles explain the ability of clays to hold large amounts of water, distributed in a very large number of tiny pores. Large amounts of water means large volume of pores.

Soil structure issues will seldom recur during topics discussed later in the curriculum in soil mechanics or geotechnical engineering courses. Instead, students deal routinely with the two aggregate measures of pore volume that are necessary for calculations: porosity (pore volume/total sample volume) and void ratio (pore volume/volume of solids).

The concept of soil structure was investigated in an environmental geotechnics course, a specialized geotechnical course often offered as an elective in the last year of a civil engineering curriculum. The environmental issues addressed in such a course make the topic of soil structure pertinent. This is because the structure of clays depends on the properties of the pore fluids: certain contaminants will affect the structure and hence the behavior of clays in undesirable ways (e.g. increase their permeability). The specific environmental geotechnics course is an advanced undergraduate course taught at the fifth year of the civil engineering program at the National Technical University of Athens (NTUA), Greece. In terms of prior instruction, students have already completed courses on soil mechanics, experimental soil mechanics and hydraulics.

The qualitative question formulated to test the conceptual understanding of soil structure reads as follows:

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

Students are further advised to support their answer mainly with personal observations (e.g. from everyday-life experiences with soil/dirt, such as playing with beach sand, or from an activity in the soil mechanics laboratory) rather than by what they can recall from instruction.

The question was initially asked during a mid-term exam. It was explained to students that the exam was mainly diagnostic and hence contributed only slightly to the final grade. In addition, it was clarified that the particular question would be graded for the richness of the justification of the opinion and not for the correctness of the answer. Although such measures seem to put most students at ease to give an answer that makes sense to them, it cannot stop those who recall instruction on clay structure to give the "right" answer.

3 PERCEPTIONS OF SOIL STRUCTURE AND IMPLICATIONS

The students' answers were an overwhelming "vote" for sand. More specifically, 28 students answered that they expect larger porosity in sands, whereas only 11 expect larger porosity in clays. (In addition, there were four students who answered "it depends", probably exhibiting the characteristic sense of discomfort many engineering students experience when faced with open-ended questions without clear-cut answers.) The explanations offered are summarized in Table 1. It should be noted that the number of explanations is larger than the number of the answers since many students provided more than one justification for their answer.

Table 1. Summary of justifications for porosity trends.

Frequency	Answer and supportive arguments
28	**Sand can have higher porosity because…**
14	…sand has higher permeability
10	…sand has larger pores
10	…sand flows, whereas clay is dense, hard
3	…sand can be compacted more easily
2	…sand dries more easily (probable implication: sand has higher permeability)
1	…forces keep clay particles closer together
11	**Clay can have higher porosity because…**
3	…clay has open structure
3	…clay can absorb a lot of water
1	…clay is more difficult to dry (probable implication: clay holds more water)
1	…clay has more cracks and hence more voids

It is instructive to identify the categories of the arguments used by the students. Most students give explanations based on observations related either to the large size of sand pores, or to a few physical characteristics of soils (e.g. sands flow), including a measure of the easiness of water flowing through soils (i.e. permeability). A few students, however, contrary to the instructions, provide arguments originating from textbooks (e.g. clay has an open structure). It may be relevant to note that from a total of four textbook-type arguments, three are employed to support the answer that clay can have larger porosity.

A striking difference between the two sets of justifications is that the number of the arguments for sands is higher than the number of the respective answers. This indicates that the students are pretty confident about their "sand vote" since they can support it with more than one explanation (an average of about 1.5 explanations corresponds to each of the "sand votes", twice as much compared to the "clay votes"). On the contrary, the arguments for clay are fewer than the answers and are less well phrased, implying that students recalled the correct answer and then groped for explanations. In fact, one is tempted to posit that students follow the same procedure for arriving at either one of the two answers: they hold a mostly unexamined belief (either through everyday-life experiences, or through instruction) and then search for arguments to support it, rather than the other way round. It is characteristic that the exact same argument is used to support both answers: the fact that sand dries more easily than clay is used as an argument both for sand (apparently focusing on higher permeability and, supposedly, higher porosity) and for clay (apparently interpreting the difficulty as an indication of clay holding more water and hence having higher porosity).

The belief that sands can have higher porosities than clays has also been found to be prevalent in an undergraduate soil mechanics class in another institution (Pantazidou 2001). There the question was asked in the format of "split task" assessment: the students were asked both about the "right" answer and whether their experience confirmed that answer. Some students answering correctly that clays can have larger porosity, specifically noted that experience told them otherwise.

4 INSTRUCTIONAL INTERVENTIONS

The answers of the students point to two kinds of misconceptions the instructor must address. The apparent one is reversing the belief that sands can have larger porosity, whereas the opposite is true. It should be noted here that students do have resources available that tell them otherwise. These include classic soil mechanics reference books, such as the one by Lambe and Whitman (1969), which includes a table with values of porosity for sands (with a maximum of 0.55), as well as a discussion later in the text on the possibility of soft clays to have much higher porosity. The same is true for the two soil mechanics textbooks available to NTUA students (Gazetas 2001; Kavvadas 2002). However, it is doubtful whether students pay much attention to information in textbooks about typical values expected for key parameters, having become accustomed to an assessment practice whereby any numbers needed are always given to them and hence understandably concluding that "the quantification of their personal experience is unnecessary and irrelevant" (Redish and Smith 2008).

It seems that students need something more memorable than tables with numbers to appreciate the potential of clays to have large pore volume, perhaps a model of a physical process. Such a learning tool would simulate soil deposition by introducing soil particles at the top of a container full of water and let them settle at the bottom, attaining a configuration determined by the forces exerted among particles. A comparison between two deposition sequences starting with clay and sand particles with the same volume of solid material would show that a clay deposit can end up being "taller". The ideal software would magnify the invisible-to-the-naked-eye clay particles (making the correspondingly magnified particles of a fine sand the size of marble balls) and allow for interactive modification of the pore-water properties.

Unfortunately, although it is doable to simulate deposition of sand particles, our knowledge of the behavior of clays is not adequate to simulate deposition of clay particles at the scale of the pore level. Luckily, we can demonstrate these effects physically by letting a clay-water mixture and a sand-water mixture (with the same volume of solids) settle in volumetric tubes and observe the final volume/height of the soil. This is an extension of similar demonstrations used to show the effect of pore-water properties on the final volume of a clay sample and, indirectly, on the arrangement of the clay particles (Lambe and Whitman 1969). The corresponding laboratory demonstration is shown in Figure 1. If such a demonstration is incorporated in instruction, it may be possible to provide for some students a reminder more memorable than numbers; its power to enable conceptual change obviously remains to be investigated. Compared to the software described above, it is too static, since it does not allow manipulation of the properties of the soil and the pore fluid, nor permit any kind of prediction.

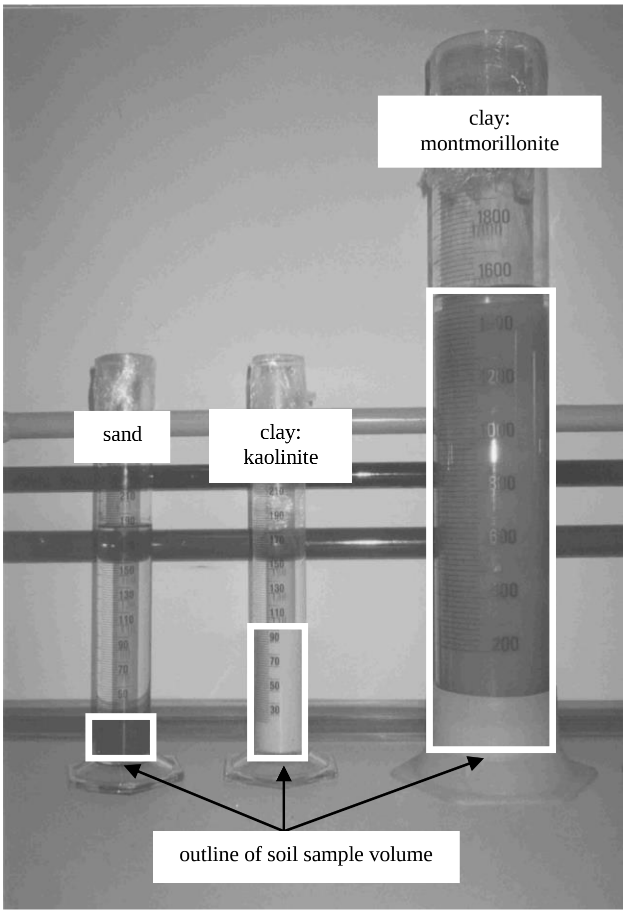

Figure 1. Soil samples produced through settlement of 40 grams of: sand, kaolinite and montmorillonite, with porosity values equal to 0.44, 0.85 and 0.99, respectively.

In addition to addressing the clay-sand misconception, the instructor has to deal with two persistent underlying misconceptions, namely that larger pores is equivalent to higher porosity and that higher permeability entails higher porosity. The first misconception can be partly a logical oversight: many small pores can win over fewer larger ones. However, the author's experience with students' answers suggests that the main culprit is paying more attention to the logical conclusion that larger particles create larger pores among them and less to the proportion of the pore/total (or pore/solid) space. A simple numerical calculation of porosity of two model porous materials created by a simple cubic packing of spheres, such as those shown in Figure 2, can demonstrate that porosity (n) in such geometrically regular particle arrangements is independent of particle size and, therefore, of pore size.

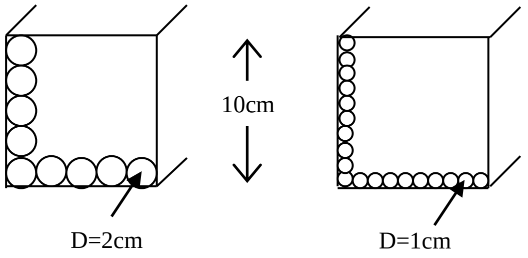

Figure 2. Cubic arrangements of spheres of unequal diameter (D) with the same porosity (n=0.48).

The second persistent underlying misconception is more related to hydraulics than soil mechanics, as the easiness with which water flows is related to the square of the radius of the pore through which water flows and not to the total pore volume. Model porous materials can again be employed to dispel this misconception. By modeling the pore space of two soil columns (A) and (B) with a bunch of cylindrical tubes of unequal radius (R), the cross sections of which are shown in Figure 3, it is easy to show that two soils of the same porosity (n) can have different values of permeability (k).

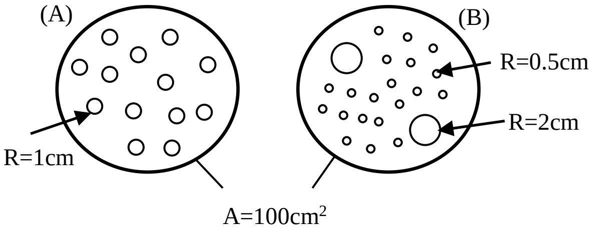

Figure 3. Models of soil columns with equal porosity ($n_A=n_B=0.41$) and unequal permeability ($k_B=2.6\times k_A$).

It should be stressed that the author has assigned as homework in various classes the calculations of porosity (Figure 2) and permeability (Figure 3) with no significant effect on the answers of students to the clay-sand question. This observation is in line with literature showing that students' knowledge is not applied consistently in different contexts (Streveler et al. 2008). A more promising approach appears to be inviting students to critique answers such as those summarized in Table 1, in lieu of expecting the question asked to mobilize seemingly dormant pieces of knowledge. Whereas students are reticent in commenting on statements made by the instructor, they become uninhibited when asked to comment on statements made by students like them. The contents in Table 1 were able to create a very lively discussion in class, when students were prompted to say with which argument they agreed or disagreed more. In fact, some students were able to make the connection between the assignment depicted in Figure 3 (which was given earlier in the semester) and the fallacy of the statement that higher permeability entails higher porosity. However, systematic research is needed to evaluate the potential of each intervention to promote conceptual change.

5 CONCLUDING REMARKS

Instructors traditionally learn about the learning experience of their students indirectly, through the students' performance. To this tradition this paper adds the systematic instructor learning that results from analysis of answers to suitable qualitative questions, formulated to probe how students understand fundamental engineering concepts.

Investigation of the concept of soil structure demonstrated that students overlook the potential of clays to have very large pore space. This has significant practical implications, as large pore space also entails a high compressibility and deformation potential, which by association students may also overlook. Hence, interventions such as the ones proposed herein are necessary.

This article was written partly with the aim of serving as a "call for action" for the geotechnical community, in order to collectively produce qualitative questions suitable for probing students' understanding of key concepts. These questions will identify students' difficulties and these difficulties will become a guide for producing new instructional techniques and tools, from class debates to laboratory demonstrations. In fact, many existing demonstrations (Elton 2001) would be more effective with a tighter connection to specific identified misconceptions, whereas a few laboratory activities have already been developed to address specific conceptual difficulties (Burland 2008).

ACKNOWLEDGMENTS

The author thanks the students at NTUA for their open-mindedness and lively participation in the environmental geotechnics course and Mr. George Pirgiotis for setting up the soil columns in Figure 1.

REFERENCES

Bowden, J. and Marton, F. 1998. *The university of learning: Beyond quality and competence in higher education*, Kogan Page Ltd., London, UK.

Burland, J.B. 2008. Personal reflections on the teaching of soil mechanics, *1st Int. Conf. on Education and Training in the Geo-Engineering Sciences*, Constanza, Romania, June 2–4.

Elton, D.J. 2001. *Soils Magic*, ASCE Geotechnical Special Publication No. 114, ASCE Publications, Reston, VA.

Gazetas, G. 2001. *Soil Mechanics*, Edition 2.4, NTUA Publications, Athens, Greece (in Greek).

Kavvadas, M. 2002. *Soil Mechanics*, NTUA Publications (in Greek).

Lambe, T.W. and Whitman, R.V. 1969. *Soil Mechanics*, John Wiley, New York, NY.

Pantazidou, M. 2001. Instructional theory, engineering education and geotechnical engineering: Common links, *4th Hellenic Conference on Geotechnical and Geoenvironmental Engineering*, Athens, May 30-June 1, pp. 25-30 (in Greek).

Redish, E.F. and Smith, K.A. 2008. Looking beyond content: Skill development for engineers, *J. of Engineering Education*, Vol. 97, No. 3, pp. 295-307.

Steif, P.S. 2004. An articulation of the concepts and skills which underlie engineering statics, *34th ASEE/IEEE Frontiers in Education Conference*, Savannah, GA, Oct. 20-23, Paper No. T1A-1.

Steif, P.S. and Hansen, M.A. 2007. New practices for administering and analyzing the results of concept inventories, J. of Engineering Education, Vol. 96, No. 3, pp. 205-212.

Streveler, R.A., Litzinger, T.A., Miller, R.L. and Steif, P.S. 2008. Learning conceptual knowledge in the engineering sciences: Overview and future research directions, *J. of Engineering Education*, Vol. 97, No. 3, pp. 279-294.