THE SCHOLARSHIP OF TEACHING:
A CASE IN ENVIRONMENTAL GEOTECHNICS

Contents

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THE SCHOLARSHIP OF TEACHING: A CASE IN ENVIRONMENTAL GEOTECHNICS

Marina Pantazidou[1]

ABSTRACT

After a short introduction on the framework of the scholarship of teaching and on the thematic field of Environmental Geotechnics, this article presents elements of an environmental geotechnics course developed within this framework. The article highlights in particular educational materials informed by research on learning, such as questions developed to probe student understanding of key concepts and interventions designed to address identified misconceptions. The article also discusses how modeling is incorporated into instruction, an innovation made possible by prior research on the task of modeling and by the existence of educational software that facilitates comparison of alternate modeling decisions. In addition, the article describes demonstrations that complement instruction and assignments that test student ability to apply material from the course in a wider context. Claiming that the scholarship of teaching must become a collective undertaking, in order to bring about improvements in education that take into account results of research on teaching and learning, the article concludes with recommendations that enable contributions from the wider academic community.

1. INTRODUCTION

Neither the wider academic community, nor the education research community has succeeded in developing transferable educational "technologies" as successful as the textbook, despite the availability of numerous computer-based and web-based applications. While very few faculty members undertake writing their own textbook, all are on the lookout for a good textbook and exchange with colleagues relevant comments and experiences. If we make the popularity and the transferability of textbooks the standard of success of educational materials produced, then we must also create avenues for publicizing new materials.

This article seeks to encourage critical public sharing of experiences engineering instructors may have with successful introduction of educational materials in their courses (see Sections 2.4 and 2.5 for examples). The article is written with two audiences in mind. First, instructors of courses on environmental geotechnics and related subjects, who may find some of the material presented herein useful for their own class (this audience may be more interested in Sections 2.1, 2.3.2, 2.4 and 3). Second, engineering instructors who may draw analogies with their own course and who may, as a result, get motivated to share their own tactics in enriching their classes

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(Sections 2.2, 2.5 and 4 may be of more relevance to this audience). It is hoped that both audiences may eventually contribute publicly to identifying needs in teaching specific engineering topics and to showcasing interventions developed by them or others.

The aforementioned contributions are not customarily thought of as an integral part of faculty public duties. For a change of this mindset, two breaks from tradition appear necessary. The first is taking university teaching beyond the confines of a group affair, the group including the instructor and the enrolled students, and into a public sphere, similar to how research is conducted. The second needed change is providing the “stage” necessary for the public aspects of teaching to become visible. This latter requirement will be discussed at the summary section of this article. The former requirement has been advocated through the framework of the “Scholarship of Teaching”, which is the topic of the next section.

1.1 Scholarship of teaching

The scholarship of teaching has been discussed and supported for the last 20 years in the writings of key figures in tertiary education, such as Ernest Boyer (1990) and Lee Shulman (e.g. Hutchings and Shulman 1999), to be elaborated most recently specifically for engineering education (Shulman 2005; Borrego et al. 2008). Collectively, these authors present their ideas in a continuum that covers teaching, scholarly teaching, the scholarship of teaching and research in engineering education. The following clarifications are adopted from Borrego et al. (2008). *Scholarly teaching*, except from good content and teaching methods, involves classroom assessment and evidence gathering informed by best practice. It also encourages collaboration and review. The *scholarship of teaching* is public, open to critique and evaluation, and results in products that others can use and build on. Moreover, it involves inquiry and investigation, focusing particularly on student learning. Finally, *research on engineering education* shares the characteristics of scientific inquiry: it poses research questions, interprets the results in light of theory and pays attention to the design of the study and the methods used. It is encouraging to note here that, with time, research on engineering education is increasingly carried out by discipline-based education researchers (including engineering faculty), who are not or at least have not started as cognitive scientists or education specialists, following a trend already observed in physics education (Redish 2000).

It must be made clear that the arguments in favor of university professors becoming more open with their teaching are not confined any more to publications and institutions that deal solely with education, such as education journals and education foundations. Among the most authoritative voices joining in the support for a scholarly attitude to teaching is that of Derek Bok (2006), past president of Harvard University for over 20 years, who encourages professors to deal with issues of quality university education with the same care they confront propositions in their own scholarly work. Most relevant to the present article, Bok (2006) notes the neglect on the part of faculty members to take into account research on teaching and learning in preparing their classes. Increased use of computers and the Internet can be considered to be improvements of the delivery medium, which do not though lead automatically to improvements in learning (Dutton et al. 2001; Steif and Dollár 2009).

Within this framework as a background, the instruction of an environmental geotechnics course is discussed by highlighting application of best practices and describing activities and interventions developed specifically for this course. The next section gives a short introduction on the thematic field of Environmental Geotechnics, for the benefit of a reader unfamiliar with it, before the article focuses on the particular course.

1.2 Environmental geotechnics

The thematic field of Environmental Geotechnics, or Geoenvironmental Engineering, combines principles from contaminant hydrogeology and geotechnical engineering to address problems related to the protection and restoration of the geoenvironment. Typical applied problems include subsurface characterization, soil and groundwater remediation, as well as waste containment. Courses on Environmental Geotechnics are commonly offered either as elective courses in undergraduate civil engineering curricula, or as graduate courses. An environmental geotechnics course may focus more or less on the geotechnical aspects of waste containment, depending on the background of the instructor and on the academic unit (geotechnical or environmental) offering the course. Hence, course contents are expected to place different weight to the various topics of Environmental Geotechnics. However, as it will be discussed below, contents only partially mirror a course in the absence of detailed learning outcomes.

2. AN ENVIRONMENTAL GEOTECHNICS COURSE AT NTUA

The author of this article is an instructor of an environmental geotechnics course, which she has strived to develop, deliver and disseminate within the framework of the Scholarship of Teaching. She has been teaching comparable versions of the same course, as a graduate or advanced undergraduate course in two institutions in the US and Greece, for 14 years. The current version of the course is taught at the final year of the five-year undergraduate civil engineering curriculum of the National Technical University of Athens (NTUA), Greece. At the School of Civil Engineering at NTUA, the first six semesters are common for all students. During the remaining semesters, students enroll in increasingly fewer common courses, concentrating more and more on courses from one of four specializations: structural, transportation, hydraulic and geotechnical engineering. During the last semester, students work on their thesis, typically in the area of their specialization. Upon graduation, students are awarded a common degree in Civil Engineering, regardless of their elected emphasis.

For the 9th semester of the geotechnical specialization, students must choose four courses from six core electives: environmental geotechnics is one of these six electives. For the students of the other three specializations, environmental geotechnics is an elective belonging in a wide pool from which students choose 1 to 3 courses. The combined result of curricula constraints and course scheduling is that the majority of the enrolled students belongs in the geotechnical specialization, with a small representation of students from the hydraulics specialization. Hence, enrollment varies with the temporal popularity of the geotechnical specialization and ranges between 30 and 50 students.

In summary, the environmental geotechnics course described herein is an advanced undergraduate course, taught to 5th year civil engineering students, most of whom have completed a sizeable number of geotechnical courses. While all civil engineering students have courses on engineering geology (two courses), soil mechanics (two courses) and foundations, students following the geotechnical specialization also have completed a course on experimental soil mechanics, and, most of them, on soil improvement and soil-structure interaction as well. Because the students have the maturity expected in master-level programs, the instructor can design a suitably challenging course, without diverting time to bringing all students to the same level, since they have all followed the same basic curriculum.

2.1 Learning outcomes

The course has been designed from an applied perspective. Given that environmental geotechnics is an applied topic, the course includes the basics needed so that a civil engineer with the background of the course can contribute to the characterization and remediation of a contaminated site or to the design of a landfill liner.

The aim of the course is described in terms of learning outcomes that guide all assessment activities, both for diagnostic purposes, in quizzes and in-class activities, and for final grading. The detailed statement of learning outcomes also enables other instructors to judge whether material developed may be of use to their courses, an evaluation that cannot be made on the basis of course contents alone. This is an important point that will be revisited at the closing of this section.

The overarching goal of the course is to develop environmental thinking related to (i) assessing the severity of a contaminant release in the subsurface, (ii) recognizing the physical-chemical-biological mechanisms that affect the fate and transport of the released contaminant and, (iii) selecting appropriate remedial measures and/or technologies. The goal of the course is mapped to the learning outcomes listed in Table 1. Course contents are listed in Table 2.

Table 1. Learning outcomes of environmental geotechnics course.

	The goal is achieved if at the end of the course the students:
(1)	can locate reliable data on the effects of contaminants on human health;
(2)	are confident in applying principles of groundwater flow, mass transfer and solute transport to problems of contamination and restoration of the subsurface;
(3)	are able to address the geoenvironmental aspects of landfill and clay barrier design;
(4)	are familiar with a wide range of remediation technologies;
(5)	are able to take initiatives related to modeling, i.e. related to the formulation of a simplified problem that admits solution;
(6)	are aware of some social or public policy dimensions of the problems of subsurface contamination and restoration.

Table 2. Contents of environmental geotechnics course taught in respective semester weeks.

	Topic	Week
1	Cases of contaminated & remediated sites	1
2	Legislation	2
3	Sources and characteristics of contaminants	2
4	Risk assessment	3
5	Groundwater flow, unsaturated flow, multiphase fluid flow	4-6
6	Soil-contaminant interaction	7
7	Mechanisms affecting the fate of contaminants	8
8	Solute transport applications (includes practice in the use of educational software in the School's computer lab)	9-10
9	Landfill liner design and materials	11
10	Remediation technologies for contaminated sites	12-13

It is apparent that there can be no one to one correspondence between a set of learning outcomes and a set of course contents. For instance, the particular learning outcomes listed in Table 1 specify different levels of student performance for each sub-goal (are aware… familiar… able… confident). In addition, some key sub-goals can be further prescribed in terms of level of performance (e.g. see discussion of modeling performance in Section 2.5). Hence, both sets are needed to fully describe a course and allow instructors to judge similarity of courses with the same name or with a comparable list of contents.

2.2 Probing students' understanding

During the planning stage of a course, it is recommended that the instructor come up with techniques to identify the pre-formed concepts that students bring to instruction. At this point, it is necessary to differentiate between contents of prerequisite courses, nominally the same for every student progressing through comparable curricula, and concepts formed by each student as a result of prior instruction, even before college, and often in combination with everyday life experiences.

The distinction between contents of prerequisite courses and pre-formed concepts is important for all domains and particularly so for many branches of engineering. Civil engineering is part of everyday life: we all have many personal experiences with soil and with moving water, while most have seen landslides, cracks in buildings, etc. This is a feature civil engineering shares with physics, for which education research has shown that students of all ages enter courses with mental constructs of some explanatory power as to how things are or work (Redish 2000). To these constructs, new constructs are continuously added throughout formal education, with better or worse fit or, even, in unidentified conflict. Instruction must start with identifying loose-fitting or conflicting concepts, if it aims at bringing about solidly founded change. 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.

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. Bowden and Marton (1998) discuss a number of studies that have developed qualitative questions to diagnose "pre-conceptions" (what students bring to instruction) 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. More importantly, these questions often serve as mirrors that reveal to the students themselves how they have organized knowledge. The remaining of this section gives examples of questions and corresponding misconceptions, while interventions designed to address identified misconceptions are discussed next (Section 2.3).

The questions developed to probe students' understanding deal with topics such as groundwater flow, soil structure, as well as key components of mass transfer and contaminant transport. The answers of the students can feed discussions in subsequent courses, where students are invited to comment on them. Sometimes, class discussion takes turns that suggest further topics and questions suitable for exploration. The author's experience has shown that while some misconceptions can be anticipated, others come as a complete surprise, as will be discussed below.

2.2.1 Groundwater flow

Students come to the environmental geotechnics class with a course in hydraulics and the groundwater flow component of a soil mechanics class. To gauge the degree to which students have integrated elements from prior instruction, a basic question is asked in two alternative ways:

> "What makes (ground)water move? Under what circumstances does water remain immobile?"

This question is asked at the very beginning of the course. The answers compiled through the years are being "played back" to the students for comments when concluding instruction on groundwater flow.

The answers to this simple question reveal several half truths and misconceptions. The non-technical phrasing of the question frees many students to revert to what they really believe as true, despite what they have learned and even remember as being correct. Many students simply answer "gravity" or "pressure", although the same students can give the correct form of Bernoulli equation, with all three components of gravity, pressure and velocity. This is evidence of superficial integration of concepts.

Even students who invoke hydraulic head fail to grasp the generality of the concept, as evidenced by answers that read as follows. "Groundwater moves due to differences in hydraulic head between two points. In addition, water also moves as a result of capillary phenomena." Or, [groundwater moves due to] "difference of energy levels between two points, plus capillary phenomena". The students fail to appreciate that hydraulic head encompasses capillary phenomena through corresponding changes in water pressure. One student even forgot the hydrostatic distribution, and answered to the second question "when the permeability of the soil is very small".

2.2.2 Contaminant sorption to the solid phase

The questions that never fail to reveal students' beliefs are those asking for preferences or judging whether something is "good" or "bad", without alluding to potential criteria used for judgement. For example, we may ask for a parameter X, related to a phenomenon or a property Y, "do you prefer X to have a high or a low value?", in order to probe students' understanding of Y and its implications. Such a question was asked about the partition coefficient, or distribution coefficient, which relates the concentration of a dissolved contaminant in groundwater to the concentration of the contaminant sorbed to the solid phase, provided that equilibrium is assumed between the aqueous and solid phases. The answer of a student reads as follows. "Because we cannot decontaminate the solid phase, we prefer to have a larger proportion of the contaminant mass dissolved in groundwater rather than sorbed to the solid phase" [and hence we prefer a small partition coefficient]. In a theoretical world, where equilibria are instantly achieved, the student's answer would be "wrong". In reality, the student has grasped an important point for remediation. However, the student did not consider a contaminant release scenario, where a lower partition coefficient corresponds to lower retardation factor and, hence, faster spreading of the contaminant.

2.2.3 Nature of dissolved contaminants

This final example did not originate from a probing question phrased by the instructor, but instead came about serendipitously in class. In a discussion about contaminated water moving in the unsaturated zone, the following analogy to watering a flowerpot was used. "We know that if we give just a little water to the plant, all water is held in the soil pores. As we give more water, it finally drains through the bottom of the pot. Like in a flowerpot, if a large volume of contaminated water escapes, it will finally reach the water table". At this point, a student remarked that the analogy was not a good one, because at a contaminated site the movement of [contaminated] water would reduce the permeability of the soil. This remark baffled the author of this article, as it could not be accounted for by the "half truths" revealed by her students in earlier years. Upon further questioning, it became evident that the student's mental construct for contaminated water was akin to water carrying the dissolved contaminants like solid particles in suspension (when unraveling the confusion reached this point, then the instructor identified similarities with misconceptions of other students). This mental construct makes the remark understandable: as this imagined contaminated water flows through soil, the particle-like molecules of the contaminant get stuck in soil pores, gradually clogging them and, hence, reducing permeability.

The examples in Sections 2.2.1 to 2.2.3 show that when students are asked to answer open-ended, simply-phrased qualitative questions and are given chances to contribute to free-form discussions, it becomes more probable that they will share their true beliefs about phenomena. This is supported both by the teaching experience of the author and the literature. In fact, some students understand the two different tracks they have been moving and ask "do you want me to tell what I really believe or to give the correct answer"? (Mazur 1997). If the students trust that the instructor does not mean to trick them, they will give candid answers, to the benefit of all.

2.3 Addressing student misconceptions

Some misconceptions are mere misunderstandings, which can be dispelled with some clarifications and carefully chosen terminology. Others are deeply rooted and require targeted interventions. Hence, in addition to the need for phrasing qualitative probing questions, the educational community of each domain must also come up with suitable interventions and then assess their effectiveness. Most probably, help from education researchers will be necessary for a systematic assessment. This section gives two example problems and offers suggestions for addressing them, while stressing the lack of any systematic assessment.

2.3.1 Piezometric surface: a potentially misleading term?

Piezometers are used to measure pressure at the point they are installed. The surface created by the points corresponding to the water surface in each piezometer is sometimes called “piezometric surface” and is depicted on maps with lines of equal elevation. Some textbooks even introduce the term “piezometric head” for the sum of pressure head plus elevation head (e.g. Munson et al. 2002, page 134). At the water surface in a piezometer, the water pressure is zero (atmospheric). Hence, the height of the column in the piezometer is the total hydraulic head at any point within the piezometer, including the point within the aquifer it was installed. In other words, piezometers give us all the information we need to tell where is water flowing within the aquifer. Now, a casual reference to the above may also leave a student with the impression that, since we use the piezometric surface/head to study the movement of water, pressure is the quantity that determines how water moves or, in simple terms, “makes water move”. At this point, this is a hypothesis, which becomes though an even more probable scenario for Greek students, to whom the Greek-origin terms “piezometer” (πιεζόμετρο = pressure meter), “piezometric surface” and “piezometric head” are more easily understandable in their literal sense. In view of the number of students who consistently answer “pressure” to the question “what makes water move”, the author recommends that the terms “piezometric head” and “piezometric surface” be not used. To replace the latter, the term “surface of equipotential lines” is preferred or, if something shorter is absolutely necessary, “potentiometric surface”.

2.3.2 Soil structure

Student understanding of the concept of soil structure has already been discussed elsewhere (Pantazidou 2009). Only a brief summary will be provided herein, in order to demonstrate the guidance provided by the analysis of the students’ answers for implementing suitable interventions. The relevant probing question used 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 students' answers were an overwhelming "vote" for sand (28 answers for sand versus 11 answers for clay). 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).

The identification of a misconception together with the identification of the justification for the misconception allow the instructor to design suitable interventions. For this particular misconception, the author built experimental models made of sand and clays. Specifically, three soil samples were created in volumetric tubes through settlement of the same weight of dry solids of sand, kaolinite and montmorillonite, which reached a final porosity of 0.44, 0.85 and 0.99, respectively (see Figure 1). Hence the students have a concrete example of two clays with much higher porosity than sand.

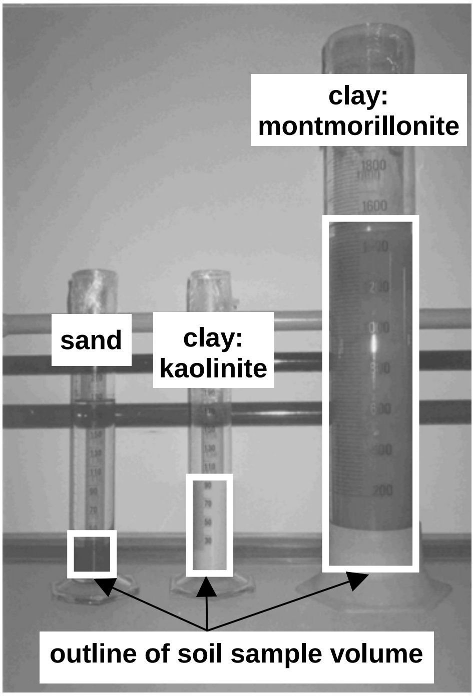

Figure 1. Soil samples produced through settlement of 40 grams of: sand, kaolinite and montmorillonite, with porosity values equal to 0.44, 0.85 and 0.99, respectively (Pantazidou 2009).

In addition, two pore models are introduced in class. One model compares two cubic arrangements that (i) are made of same-size spheres of two different diameters and (ii) have the same porosity: this model is an attempt to address the misconception that soils with larger pores also have larger porosity. In the other intervention, two soil columns are modeled as a bunch of cylindrical tubes. The columns have equal porosity but unequal permeability: this model is an attempt to address the misconception that soils with larger porosity always have larger permeability. For further details on the models, the reader is referred to Pantazidou (2009). As far as using the interventions in class, what has been most successful is incorporating the models in course components (lectures, assignments) throughout the semester. Then, at the conclusion of instruction on clay structure, the instructor can ask students to critique arguments given by students in previous years on the clay-sand question (Pantazidou 2009). These are mere suggestions at this point, however, since the success of the interventions has not been systematically assessed.

2.4 Materials developed/used in class

Up to this point, the discussion focused on probing student understanding of specific concepts and seeking solutions to address related misconceptions. This section discusses three in-class "experiments", developed mainly to enliven instruction (2.4.1 to 2.4.3), an analogy between rubber duck races and mechanical dispersion (2.4.4) and one existing visualization tool (2.4.5), the likes of which are very much needed in instruction.

2.4.1 Solute transport phenomena discussed with the aid of instant coffee

This demonstration is related to a set of probing questions asked at the very beginning of the course (together with the groundwater question of 2.2.1). The questions read as follows:

> "(A1) Describe what happens (or what we observe) when we add a few granules of instant coffee in a glass full of water, without disturbing the glass in any way. (A2) If you happen to know, write the name of the physical mechanism accounting for what we observe."
>
> "(B) If we stirred with a teaspoon the glass of the previous question, how would your answers to (A1) and (A2) change?"

Depending on the flow of class discussion, the demonstration with instant coffee is made at the beginning of the class, when some students reply "diffusion" to (A2) – while no one has ever answered advection to (B), or/and at the beginning of instruction on solute transport, when the connection of the spoon stirring with advection has more chances to stick. This simple experiment is easy for any student to repeat at home. Here it must be added that the instructor has repeated a few times the experiment in her kitchen, but never managed to get a completely homogeneous distribution of coffee in the unstirred glass by diffusion alone: a more intense brown color still remains close to the glass bottom by the time when a lot of the dilute coffee has evaporated and the glass must be washed to avoid risking permanent stains.

2.4.2 Mass transfer in shot glasses

Instruction on mass transfer and equilibria between phases is one of the most rewarding parts of environmental geotechnics, because it affords the possibility to unify in a single framework various phenomena students are very familiar with from prior instruction and everyday life experiences, such as evaporation and dissolution. Students have no conceptual difficulty starting from evaporating fluids and equilibrium between (a) a gas and a pure liquid, and then move to equilibria between pairs of (b) a gas and a mixture of liquid organic contaminants, (c) a gas and contaminated water, and (d) water and nonaqueous phase liquid (NAPL) or water and NAPL mixtures. Some students, however, initially at least, have difficulty in including in the same framework equilibria between liquids/gases and a solid phase. A demonstration with various liquids in shot glasses (Figure 2) can help with the transitions from familiar to unfamiliar interactions between phases.

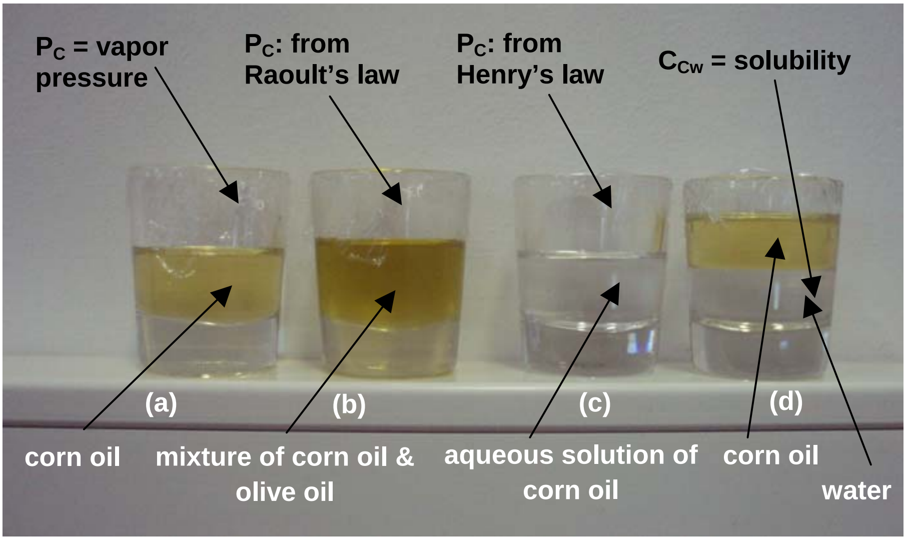

Figure 2. Shot glasses demonstrating possibilities of phase interactions and making the connection with respective physicochemical parameters (P_C = pressure of corn vapors in the gas phase, C_{Cw} = concentration of corn oil in the aqueous phase).

Figure 2 shows the shot glass collection used in class. From left to right, we have (a) corn oil, (b) a mixture of corn oil and olive oil, (c) an aqueous solution of corn oil and (d) the immiscible pair of water and corn oil. Each shot is discussed separately to make the connection with the corresponding parameter, namely, vapor pressure [for pure liquid in (a) and liquid mixtures in (b)], Henry's Law constant [for (c)] and solubility [for (d)]. The affinity of each phase for its neighbor is associated with high values of the corresponding parameter. Then the instructor can ask:

> "We explored how each phase interacts with its neighboring fluid. How about the neighboring glass? Any interaction with the glass walls?"

If these questions fail to draw any response, then the instructor may point to the students what happens when we try to wash (by hand, not in the dish washer!) tupperware used for storing greasy/oily food (lots of detergent and several passes with the washing sponge), before asking:

> "What about the interaction between the greasy juices of the food and the plastic walls of the tupperware?"

At this point several students start nodding, realizing the inconvenient affinity of oil and grease for plastic food containers.

There is no denying that these demonstrations and questions could appear, at first, a little trivial for an advanced engineering course addressed to high-achieving 22- and 23-year olds. That's why they are perhaps best presented with a dose of amusement, as if saying "come on, indulge me with something really too simple for you". The students catch on and, whether they learn better or not, the resulting atmosphere in the class is very pleasant.

2.4.3 In-class "transport experiment": "sorption" affects mobility of chocolates

This demonstration requires some planning, as the instructor must purchase in advance a good number of individually wrapped bite-size chocolates. It is easier to follow the description of the experiment having in mind a typical longish NTUA classroom, as the one shown in Figure 3: a classroom with several rows of tables, each row having three tables with aisles on all sides. Chocolates move through tables with specific rules towards the back of the classroom. Their progress is tracked in time steps.

Variation No 1 of the experiment goes as follows. At time zero, the tables at the front row receive the same number of chocolates, say 12. During the first time step, one front table gives to the table behind ¾ of its chocolates (9), keeping 3 [the ratio (chocolates retained)/(chocolates passed on) is 1:3 and, for the experiment's purposes, corresponds to a partition coefficient $K_p/3$]. The middle front table gives to the table behind ⅔ of its chocolates (8), keeping 4 [the ratio (chocolates retained)/ (chocolates passed on) is 1:2 and corresponds to a partition coefficient $K_p/2$]. Finally, the third front table gives ½ of its chocolates (6), keeping 6 [the ratio (chocolates retained)/(chocolates passed on) is 1:1 and corresponds to a partition coefficient K_p]. This is repeated at subsequent time steps, with each row receiving (with the exception of the front) and giving, rounding up chocolates passed on to the next integer. Students are asked to keep track of the number of chocolates at their desk, which is used to complete a table on the board, showing the progress of the experiment (see Table 3). After a few time steps, it is clear that chocolates have moved faster through the tables with the lowest partition coefficient. Using proper solute transport terminology, these chocolates are more "mobile".

Table 3. Variation No 1 of in-class transport experiment. The number of chocolates corresponds to contaminant concentration. At the front table (tbl) of each row, which corresponds to a contaminant source, 12 chocolates appear at time T=0. The experiment proceeds in 4 time steps, showing the effect of partition coefficient on contaminant spreading in space with time.

Chocolates on tables																	
Side column of tables						Middle column of tables						Side column of tables					
Partition coefficient ⅓K_p						Partition coefficient ½K_p						Partition coefficient K_p					
	T=0	T=1	T=2	T=3	T=4		T=0	T=1	T=2	T=3	T=4		T=0	T=1	T=2	T=3	T=4
tbl.1	**12**	**3**	**1**	**0**	**0**	tbl.1	**12**	**4**	**1**	**0**	**0**	tbl.1	**12**	**6**	**3**	**1**	**0**
tbl.2		**9**	**5**	**2**	**0**	tbl.2		**8**	**5**	**2**	**0**	tbl.2		**6**	**6**	**5**	**3**
tbl.3			**6**	**5**	**3**	tbl.3			**6**	**6**	**4**	tbl.3			**3**	**4**	**5**
tbl.4				**5**	**5**	tbl.4				**4**	**5**	tbl.4				**2**	**3**
tbl.5					**4**	tbl.5					**3**	tbl.5					**1**

Instructors preferring to avoid the time needed for calculating fractions may favor an alternative experiment. In variation No 2, tables in each row keep (for ever) a fixed number of chocolates and give the rest to the table behind. This variation requires more chocolates. Say that we start with 24 chocolates in each front table. One column of tables keeps 2 chocolates (partition coefficient K_p), the middle column keeps 4 chocolates (partition coefficient $2K_p$), while the third column keeps 6 chocolates (partition coefficient $3K_p$). Figure 3 shows variation No 2 at the 2nd time step, when the tables at the "contaminant-chocolate front" of the third row have 18 (K_p), 12 ($2K_p$) and 6 ($3K_p$) chocolates. Granted, variation No 2 is an even less faithful representation of solute transport, compared to variation No 1. However, students have no difficulty seeing the analogy with contaminants retarded due to sorption. In fact, upon returning the few unconsumed chocolates after the last time step, students have commented that the experiment not only models sorption but solute decay as well!

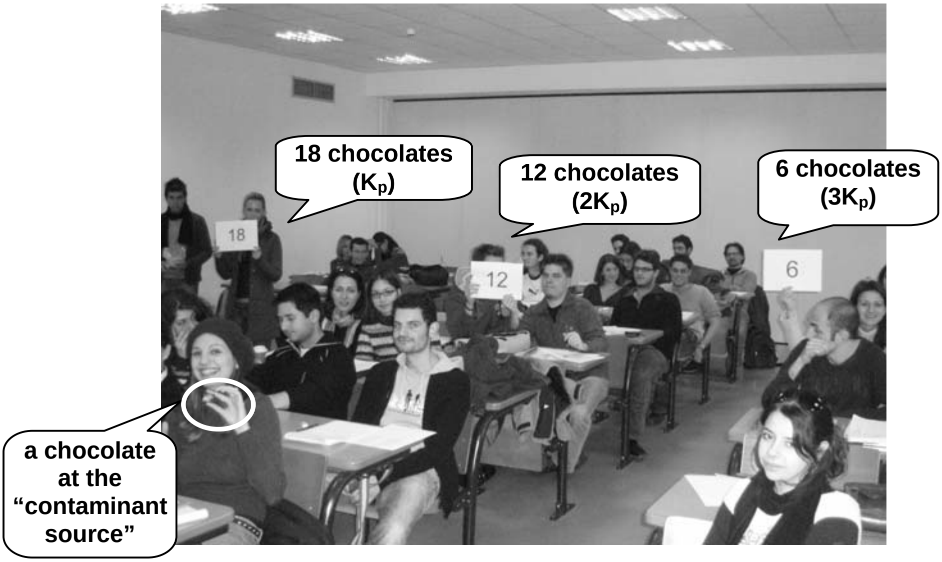

Figure 3. Variation No 2 of in-class solute transport experiment: chocolates move faster through tables with lower partition coefficient K_p.

2.4.4 A …literary explanation for mechanical dispersion

Writer David Lodge (2002) provides in his book "Thinks…" a very good analogy for mechanical dispersion. British academic life provides the backdrop to this comedy of manners. At some point in the novel, a raffle is organized in a way made possible by …mechanical dispersion! Raffle participants buy numbered tickets. The day of the raffle, numbered rubber ducks are dropped from a low bridge over the stream flowing through the campus of the novel. All rubber ducks start at the same time, but surely enough some go faster, some are left behind, just as dispersing contaminant molecules. When the first duck arrives at a set downstream point, the holder of the ticket with the same number has won the raffle. Now, of course, one could tie all the rubber ducks together to demonstrate advection (and ruin the raffle). It should be added that the analogy's literary pedigree may be questionable since, according to Wikipedia (2010), rubber duck races are internationally popular for charity purposes. In any case, duck races provide a very suitable introduction to key solute transport phenomena. It would be ideal if the verbal description of the duck race was accompanied in class by pictures of the race at various times, showing the distance between the first and the last duck continuously increasing, similar to what happens with time to the tails of the contaminant distribution. A search on the Internet for "rubber duck race pictures" gives many delightful pictures but not really suitable for educational purposes, since they do not focus on tracking duck dispersion with time.

2.4.5 Visualizing the relative contribution of transport phenomena

This class activity consists of using three videos, which are supporting material of the article by Zinn et al. (2004) “Experimental visualization of solute transport…”, published in the scientific journal “Environmental Science and Technology”. The videos show water displacing dye in a thin transparent chamber modeling heterogeneous porous media with areas of contrasting properties. Different contrasts are used in order to highlight the relative importance of transport mechanisms and their effect on tailing (or “total remediation” time). The chambers consist of a matrix of glass beads with conductivity K_m, containing circular emplacements of smaller glass beads with lower conductivity, K_e. Three conductivity contrasts are used: (i) $K_m = 6 \times K_e$, (ii) $K_m = 300 \times K_e$, (iii) $K_m = 1800 \times K_e$.

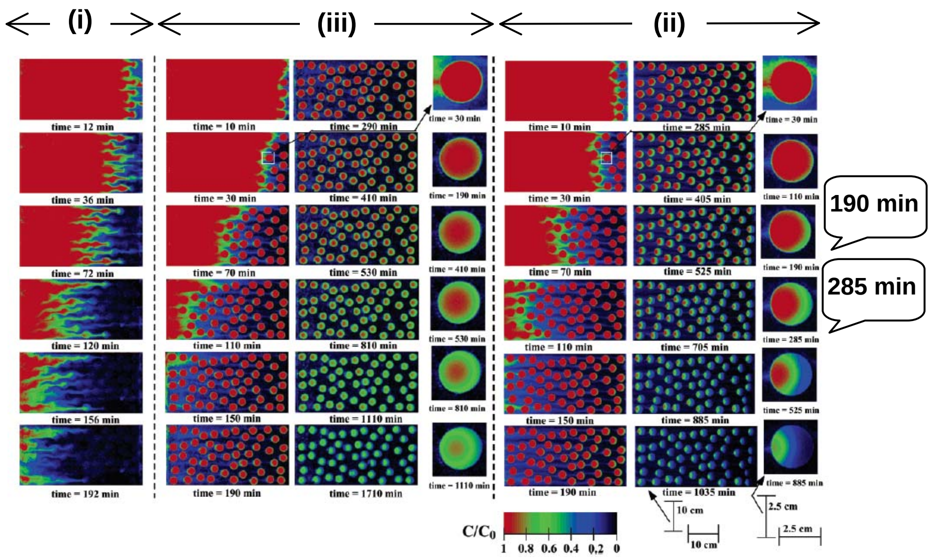

Figure 4. Color images showing evolution of concentration changes as a function of time in three chambers with circular emplacements of lower permeability: (i) 6 times lower, (ii) 300 times lower, (iii) 1800 times lower (Zinn et al. 2004, reprinted with permission by ACS).

Figure 4 shows a still picture of the video from the three chambers and zooms in selected emplacements. Flow takes place from right to left. Notice that after about three hours, chamber (i) is almost entirely clean (darkest shade prevails). At the same time, in chambers (ii) and (iii) the high permeability matrix is clean, while the low permeability circular inclusions still have high dye concentrations. As time passes, the effect of the different contrasts becomes more apparent. In chamber (ii), slow advection through the emplacements cleans the dye, as evidenced, for example, by the crescent-shape of the clean portions of the inclusions at t = 190 and 285 min. In contrast, in chamber (iii) the dye moves slowly out of the emplacements due to diffusion, as evidenced by the progressively bigger, mostly symmetrical cleaner outer ring of the inclusions. Each video lasts a few minutes. After the videos are over, the relative contribution of transport phenomena is further discussed with the aid of a PowerPoint presentation with additional results from Zinn et al. (2004). The effect of the contrast of conductivities in the three chambers is reflected in the breakthrough times of essentially clean water. Chamber (i) is practically clean after flushing 2 pore volumes. In contrast, significant tailing is observed in the breakthrough curves of the other two chambers: chamber (ii) requires flushing of 8-10 pore volumes, while chamber (iii) needs more than 12.

Many students look transfixed while watching the videos. A few times they have asked to watch the videos for a second time. This receptiveness of the students underscores the importance of supporting the development of research-quality visualization tools for education.

2.5 Modeling instruction

Although modeling of physical systems is a key engineering task, the educational literature provides little guidance on how to systematically include modeling exercises in instruction. The key role of modeling in geotechnical engineering in particular has been identified by leading researchers and revered teachers in the field (Burland 1987; 2006; Lundell-Sällfors and Sällfors 2000). In order to systematize modeling instruction, an existing modeling framework is used in the environmental geotechnics course. The methodology followed to develop the framework has been described in detail elsewhere (Pantazidou and Steif 2003; Steif and Pantazidou 2004), as well as its use in the environmental geotechnics course discussed herein (Pantazidou and Steif 2008). This article includes only the final outcome of framework development, which can be summarized with the aid of Figure 5, and some more recent experiences with modeling instruction.

Pantazidou and Steif (2003) proposed that modeling can be described (and, presumably, taught) with the aid of the following ten components. Starting from 1) *problem statement*, modeling then requires from us to determine relevant 2) *phenomena*, 3) *parameters* and 4) *variables*. It also entails decisions on elements of solution approach, which include 5) *analysis type*, 6) identification of the *region of interest*, 7) *qualitative form of solution*, and 8) *solution method*. In all of the above, which do not necessarily take place in the linear order in which they are presented, 9) *simplifications* play a very important role. Finally, the modeling task is complete, if it includes some 10) *reflections on decisions*. In the environmental geotechnics course, students are given as a handout Figure 5, which is supplemented with detailed explanatory annotations for each of the ten modeling components.

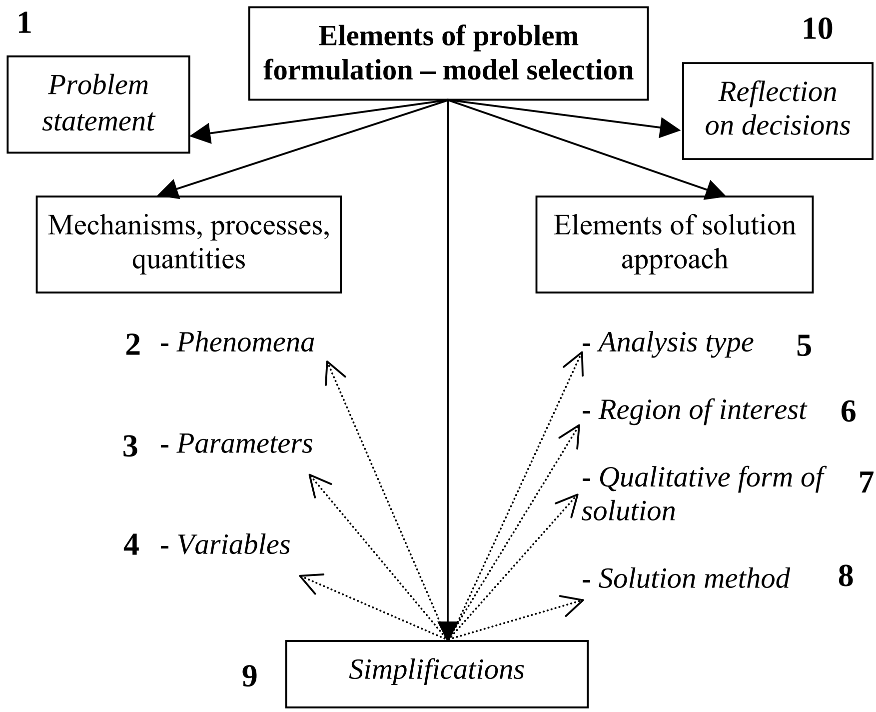

Figure 5. Constituent components of engineering modeling (Pantazidou and Steif 2008).

Perhaps the easiest entry point into modeling for students is approximations. Hence, the first introduction of students to modeling is indirect: a flow problem through a permeable barrier is discussed in class, where an assumption must be made regarding the hydraulic head at the barrier's upstream and downstream faces. In fact, a few different assumptions can be made and students identify most of them during class discussion. Solutions are carried out for each assumption. A few students are appalled by the existence of more than one possible approximations. A few others are delighted with the discussion of alternatives. In the next lecture, modeling is introduced formally, first with the aid of Figure 6 (by Lundell-Sällfors and Sällfors 2000), which shows side by side a real-life partly submerged slope and its geotechnical idealization. (Recall that most of the students enrolling in the class have selected a geotechnical specialization.) Students are then given the modeling handout and are asked to go down the ten modeling components in Figure 5 and identify those relevant to the slope problem in Figure 6. From this point onward, students are given more and more responsibility for shaping the problem they will be solving, rather than focusing mainly on analysis of fully-defined problems.

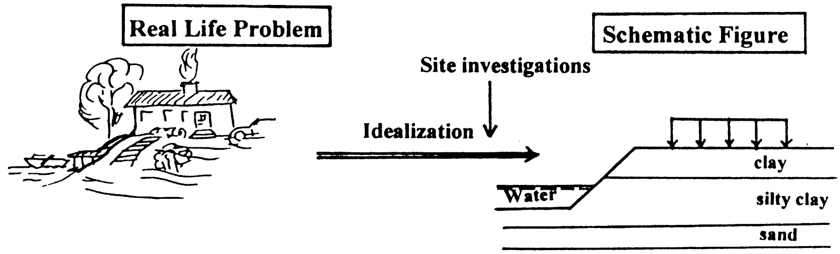

Figure 6. Modeling a real life problem (Lundell-Sällfors and Sällfors 2000).

Problems in environmental geotechnics naturally share similar difficulties with geotechnical problems, e.g. same issues with approximations of geometry and properties, reductions of dimensionality and idealizations of boundary conditions. Moreover, geoenvironmental problems offer a larger menu of phenomena (to take into account or ignore) and of corresponding parameters. In addition, they are characterized by a wider variety of initial conditions, e.g. types of contaminant releases at the source. Hence, as in many applied engineering courses, it becomes a challenging task for the instructor to bring rich "solvable" problems in class. This, in fact, is one of the two main requirements for successful modeling instruction: creating a variety of realistic problems that admit more than one solutions; the other is equipping the students with many alternative solution tools. The latter requirement is best achieved with the use of educational software. The former requirement can be partly met with restating well-defined problems as partly open-ended, paying attention to eliminate as much as possible references to variables and parameters that invariably point to a unique "right" solution.

As an example, Figure 7 shows a fully defined problem and the corresponding open-ended problem statement. The in-class discussion of problems includes first a stage of problem formulation, where students see how many modeling decisions does it take to transform a real-life question, such as (Figure 7a):

- following a contaminant spill in a pond, there is concern whether a downgradient canal may be impacted if no measures are taken

to a corresponding fully-defined assignment-type problem (Figure 7b):

- what is the contaminant travel time between the pond and the canal?

- when will 1% of the concentration of the contaminant in the pond reach the canal?

Contaminant transport is an ideal topic to introduce aspects of modeling, as there are many closed-form solutions to the advection-dispersion equation for one, two or three dimensions, for specific conditions at the contaminant source and accounting (or not) for various phenomena (e.g. sorption, decay). The use of partially-defined problems enables selective attention to specific aspects of modeling, which is consistent with learning outcome 5 defined in Section 2.1 (see also next paragraph). For example, some problems are good for deciding which phenomena can be ignored under certain circumstances. Others offer opportunities for considering reductions of the dimensionality of a problem.

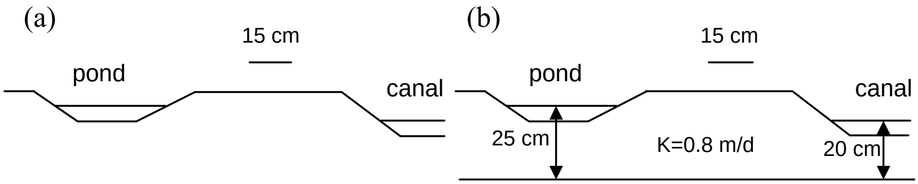

Figure 7. Comparison of (a) a partially-defined to (b) a well-defined problem (Sitar 1985).

As will be discussed below (Section 2.6.1), students also practice anticipating the effects of simplifications, with the aid of numerical modeling and comparisons of numerical solutions at different degrees of idealization with simplified analytical solutions. For this purpose, an interactive web-based (https://netfiles.uiuc.edu/valocchi/gw_applets/) educational software for groundwater flow and solute transport is introduced during instruction in the Computer Lab and used in assignments and for a term project (Section 2.6.1).

The importance of the availability of instructor-friendly and student-friendly software cannot be overstated, both for instruction in general and for modeling instruction in particular. The simulation models used in the course (Valocchi and Werth 2004) provide a prime example of a software developed by instructors who know the needs of teaching and learning. The software consists of a collection of applets that give graphical solutions to a variety of contaminant transport equations and include tutorials with the theoretical background for each equation and its solution. The software is highly interactive. The user can change transport parameters and see immediately their effect on the solution. Figure 8 shows a screen from the applet for the solution of the one-dimensional, advection-dispersion equation for a source of finite duration: the three concentration profiles correspond to different times (t) and different values of retardation factor (R). Most importantly, the developers of the software, believing in the value of their product and the value of disseminating educational material, took the time to publish an article on the software (Valocchi and Werth 2004), which is how this instructor found out about it.

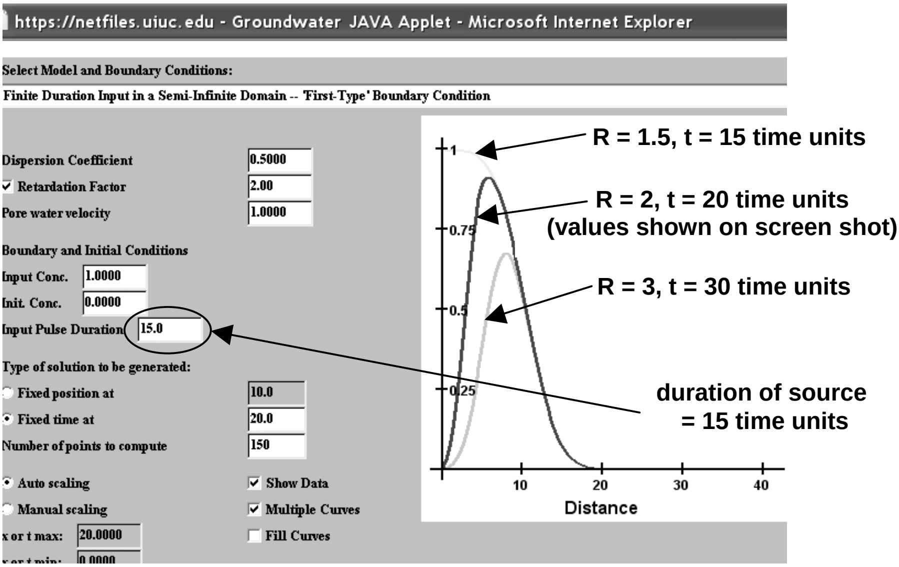

Figure 8. Sample results of interactive web simulation models: concentration profiles for 1-D transport and source of finite duration (https://netfiles.uiuc.edu/valocchi/gw_applets/).

In closing this section on modeling instruction, the learning outcome related to modeling must be further elaborated. Possible learning outcomes related to modeling may correspond to levels of student performance ranging from (i) attending to a few or most aspects of modeling of an open-ended problem, to (ii) producing a fully-defined problem statement accompanied with the information necessary for its solution, the solution itself and reflections on decisions. Based on the fundamental role of simplifications in modeling, and given the supporting role of modeling in the course under discussion, a decision was made to focus performance expectations primarily on familiarity with the simplifications aspect of modeling.

2.6 Environmental geotechnics beyond the classroom

As the course approaches the end of the semester, students must demonstrate that they are able to apply the tools and the concepts of environmental geotechnics to real or realistic problems. To this end, they are asked to work on a term project that requires significant initiative (2.6.1) and an assignment in which they are expected to demonstrate critical skills beyond those of a lay person (2.6.2).

2.6.1 Work on a term project

The term project is designed to primarily test learning outcomes 1, 2 and 5 (see Section 2.1) and also to serve as a rehearsal for consulting work. It counts for 25% of the final grade. Students are asked to perform four main tasks: (1) do some research on a specific industrial activity, (2) select the 1-2 contaminants of most concern for soil/groundwater contamination potentially resulting from that activity, (3) make up a plausible scenario of contaminant release and (4) investigate the fate of the contaminant with the aid of the educational software already introduced in class and discussed in Section 2.5 (Valocchi and Werth 2004). Students work mainly in groups of two, and each group works on a different type of industrial activity.

The list of industrial activities includes mainly installations with significant potential for air, water and land pollution, for which European legislation requires strict measures being taken for pollution prevention (Directive 2008/1/EC). It should be mentioned here that Greece lacks legislation for identifying, characterizing and remediating contaminated sites. The list is supplemented with smaller-scale activities known for creating groundwater problems, such as dry cleaners and car repair shops. Student groups select activities on a first come/first served basis. The aforementioned four tasks require significant research and analysis. To avoid devoting too much time on Task No 1, students are advised to base their project on a case study of a contaminated site resulting from a specific installation, anywhere in the world, if they are unable to locate good-quality data about potential groundwater contaminants of their selected category of industrial activity. One way or the other, groups end up with a list of several contaminants, from which they have to reason about selecting one or two for further analysis. Task No 2 is graded on the quality of their reasoning: students are given some guidance on jointly evaluating undesirable contaminant characteristics, although no uniformity is sought in this ranking process. Task No 3 is the students' opportunity of creating their own assignment and solving it as well. Significant effort is required at this stage to determine flow and transport parameters, including locating representative parameters on the fate of the contaminants, such as partition coefficients and half lives. Finally, Task No 4 consists of predicting the fate of the contaminant using different assumptions and simplifications, the effects of which are explored through some sensitivity analysis.

2.6.2 Reactions to a movie

At the very end of the course, students are given a final assignment that asks them to answer some questions after watching the film "Civil Action" (1998). This assignment specifically aims at testing learning outcome 6, but also at revealing how much students internalized material from the class, as evidenced by their thoughts about a dramatized real case.

"Civil Action" is about the highly publicized lawsuit of the citizens of Woburn, Massachusetts, against industries that were implicated in contaminating Woburn's water supply with trichloroethylene (TCE). Notable dramatic elements of the case are several deaths of children due to leukemia and the bankruptcy of the lawyer of the plaintiffs, by the end of the movie. Most importantly, the case was followed over several years by a skilled writer and the resulting book is rich with technical details (Harr 1996). While the movie is based on the book, understandably it cannot include all details. Nevertheless, it has preserved the essence of the case, which raises several difficult questions that go beyond the human-drama level.

The handout with the questions is almost two-page long and some questions do not make sense without having seen the movie. Only some questions and a few answers are included in Table 4 to give a sense of the potential of such questions to trigger thinking and reveal fundamental beliefs of students.

Table 4. Questions and related comments students give after watching the movie "Civil Action" (1998).

On monetary valuation of human life
• Necessary technical-mathematical approach (in the macroscale of society, the practical management of resources becomes necessary)
• I expected that the life of a child would be at the top of the list, not at the bottom!
What can statistics say about the high frequency of leukemia in Woburn? What do you think of the movie's analogy with coin tossing: "when you toss coins, some crowns or heads are bound to cluster together, that doesn't mean a thing".
• Wrong analogy, coin tossing is random, cancer is not.
• OK, 12 deaths (8 children) from leukemia in 15 years […] but no reference to data prior to these 15 years [implication: we have selectively and, therefore, perhaps erroneously framed the problem]
Did you change opinion about something (e.g. relevant to environmental legislation or to deciding environmental cases in court) by watching the movie?
• The presence and the role of jurors in the court made me think whether this system is "fair" or not. These thoughts made me question my own beliefs of fairness and justice. […]
• It struck me that courts do not like uncertainty […]. Something that infuriates you while watching the movie is that they did not pay attention to the opinions of experts and perhaps this happens because the experts do not inspire trust when they cannot give a single number as an answer.

The answers in Table 4 give ample evidence that students can place problems of subsurface contamination in a broader context. The answers also reveal beliefs that go beyond environmental geotechnics. For example, the question on statistics reveals some deeply held beliefs about the nature of randomness, which are worth exploring with further research.

3. AVAILABILITY OF COURSE MATERIALS

Some of the materials described herein are available in publications (Pantazidou and Steif 2008; Pantazidou 2009). All materials developed for this course are posted at the website of the environmental geotechnics class: http://users.ntua.gr/mpanta/EG.htm. The links are removed at the beginning of each fall semester, during which the course is taught, and are added gradually as the semester proceeds. This decision is made so that students check the website regularly for updates and new material (they do). The website is in Greek, as is all class material. During the summer of 2010, the material will be translated in English and be available at http://users.ntua.gr/mpanta/EnvGeot.htm.

The videos described in Section 2.4.5 are available at the website of the journal Environmental Science & Technology (ES&T) as supporting material. Permission can be granted for materials from the article itself through ES&T's website, which directs requests to the Rightslink Service of the Copyright Clearance Center (http://www.copyright.com/) for instant permission. Permission is granted at no fee, when few figures are requested in order to be printed, posted on the Internet, or reused in classroom.

The educational software described in Section 2.5, which is a key ingredient of the course, is accessible for free at https://netfiles.uiuc.edu/valocchi/gw_applets/. Once accessed, the software runs locally, but cannot be downloaded.

4. CONCLUSIONS

This article promotes a new paradigm, whereby engineering faculty contribute publicly to the improvement of engineering instruction. Such a paradigm has been made conceivable by the broadened definition of scholarship offered by Boyer (1990), which includes the scholarship of teaching, and the subsequent elaboration of his ideas specifically for engineering education (Shulman 2005; Borrego et al. 2008). Other disciplines are already making the shift, with physics leading the way (McDermott and Redish 1999; Redish 2000). However, physics is a widely-studied foundational topic, which is more likely to secure funding for education research compared to engineering subfields and, therefore, more probable to attract the attention of cognitive scientists and education researchers. Hence, contributions of faculty to the scholarship of teaching are more necessary in less widely-studied fields, such as engineering. There are many ways in which engineering faculty can contribute to the enrichment of engineering education: (i) by identifying needs, (ii) by producing themselves educational materials or (iii) by showcasing materials developed by others and used by them successfully in class.

In terms of needs, this article identified the following, giving examples in each category. Building (1) *a question bank* in order to probe students' perceptions related to key concepts and identify misconceptions. It is recommended that these questions be qualitative, phrased without technical terms and involve justifications. As shown in this article, justifications are valuable because they can give clues for developing (2) *interventions* to remedy misconceptions. In addition, the article highlighted the need for (3) *simple yet rich realistic problems* suitable for modeling instruction, as well as (4) *student- and instructor-friendly educational software* and (5) *research-quality visualization tools*.

The materials used in the environmental geotechnics course described herein fall in two basic categories. Category 1 includes materials developed or adopted with the aim of enriching instruction (Section 2.4) and helping the instructor achieve stated objectives (educational software described in Section 2.5, Section 2.6). Category 2 consists of materials designed to explore student learning and developed with guidance from results of research on teaching and learning (Sections 2.2, 2.3, modeling framework discussed in Section 2.5). Educational materials in category 1, such as demonstrations, videos, pictures, etc., are being developed by quite a few faculty, while the Internet has made them more readily available. For example, for the subject field of geotechnical engineering, which includes environmental geotechnics, see the website of United States University Council on Geotechnical Education and Research (http://www.usucger.org/). On the contrary, educational materials in category 2, such as techniques for probing student understanding, identifying misconceptions and addressing misconceptions, do not exist on the Internet, while they are rarely found in the literature. Nor are they bound to be developed spontaneously, because the production of such materials requires prior needs analysis, targeted contributions, critique and reviews.

For the aforementioned collective contributions to materialize, it is important that educators have the means to inform others and stay themselves informed on educational efforts in their subject matter. This public aspect of the scholarship of teaching necessitates the creation of a (theater) stage, or rather many stages. To this end, it is proposed that, in addition to conference proceedings and journals dedicated to engineering education, research journals in particular disciplines establish an "education corner" dedicated to the scholarship of teaching. It is also proposed that, following the example of National Science Foundation (NSF 2002), engineering funding agencies give "bonus points" to research proposals that include an educational component that addresses learning needs identified by the wider engineering teaching community and, in particular, to proposals for research visualization projects that include production of materials suitable for engineering instruction.

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REFERENCES

2008/1/EC, Directive of the European Parliament and of the Council of 15 Jan. 2008 concerning integrated pollution prevention and control.

Bok, D., 2006, Our underachieving colleges: A candid look at how much students learn and why they should be learning more, Princeton University Press, Princeton, NJ.

Borrego, M., R.A. Streveler, R.L. Miller and K.A. Smith, 2008, A new paradigm for a new field: Communicating representations of engineering education research, J. of Engineering Education, 97:2:147-162.

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

Boyer, E.L., 1990, Scholarship reconsidered: Priorities of the professoriate, Carnegie Foundation for the Advancement of Teaching, Princeton, NJ.

Burland, J.B., 1987, The teaching of soil mechanics: A personal view, Proc. of 9th European Conference on Soil Mechanics and Foundation Engineering, Dublin, Vol. 3: 1427-1447.

Burland, J.B., 2006, Interaction between structural and geotechnical engineers, The Structural Engineer, 18 April 2006: 29-37.

Dutton, J., M. Dutton and J. Perry, 2001, Do online students perform as well as lecture students? J. Engineering Education, 90:1:131-136.

Harr, J., 1996, A civil action, Vintage Books, New York, NY.

Hutchings, P. and L.S. Shulman, 1999, The scholarship of teaching: New elaborations, new developments, Change, 31:10-15.

Lodge, D., 2002, Thinks…, Penguin, London, UK.

Lundell-Sällfors, L. and G.B. Sällfors, 2000, Focus on real life problems facilitating learning and understanding, Proc. of 1st International Conference on Geotechnical Engineering Education and Training, Manoliu, I., Antonescu, I. & Radulescu, N. (Eds.), Sinaia, Romania: 425-431.

Mazur, E., 1997, Peer instruction, A user's manual, Prentice Hall, Upper Saddle River, NJ.

McDermott, L.C. and E.F. Redish, 1999, Resource letter PER1: Physics Education Research, American Journal of Physics, 67:755-767.

Montfort, D., S. Brown and D. Pollock, 2009, An investigation of students' conceptual understanding in related sophomore to graduate-level engineering and mechanics courses, J. of Engineering Education, 98:1:111-129.

Munson, B.R., D.F. Young and T.H. Okiishi, 2002, Fundamentals of fluid mechanics, 4th Ed., John Wiley & Sons, Inc., New York, NY.

NSF (National Science Foundation), 2002, Grant proposal guide, Chapter III, http://www.nsf.gov/pubs/2003/nsf032/032_3.htm, Accessed August 4, 2010.
Pantazidou, M., 2009, Student understanding of the concept of soil structure guides instructional interventions, Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering, Alexandria, October 5–9.
Pantazidou, M. and P. Steif, 2003, Modeling of physical systems: A framework based on protocol analysis, International Meeting on Civil Engineering Education, Ciudad Real, Spain, Sept. 18–20.
Pantazidou, M. and P. Steif, 2008, Modeling instruction in an environmental geotechnics course, GeoCongress 2008, New Orleans, March 9–12, ASCE Geotechnical Special Publication No. 178: 797-804.
Redish, E.F., 2000, Discipline-based education and education research: The case of physics, J. of Applied Developmental Psychology, 21:1:85-96.
Shulman, L.S., 2005, If not now, when? The timeliness of scholarship of the education of engineers, J. of Engineering Education, 94:1:11-12.
Sitar, N., 1985, Groundwater and Seepage: Class notes and assignments, UC Berkeley, Fall semester 1985.
Steif, P. and M. Pantazidou, 2004, Identifying the components of modeling through protocol analysis, American Society of Engineering Education (ASEE) Conference, Salt Lake City, Utah, June 20–23.
Steif, P. and A. Dollár, 2009, Study of usage patterns and learning gains in a web-based interactive statics course, J. Engineering Education, 98:4:321-333.
Valocchi, A.J. and C.J. Werth, 2004, Web-based interactive simulation of groundwater pollutant fate and transport, Computer Applications in Engineering Education, 12:75-83.
Wikipedia, 2010, “Rubber Duck” entry, http://en.wikipedia.org/wiki/Rubber_duck, accessed 15-2-2010.
Zinn, B., L.C. Meigs, C.F. Harvey, R. Haggerty, W.J. Peplinski and C. Freiherr von Schwerin, 2004, Experimental visualization of solute transport and mass transfer processes in two-dimensional conductivity fields with connected regions of high conductivity, Environmental Science & Technology, 38:14:3916-3926.