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Questions offering opportunities to elaborate on soil mechanics concepts

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Abstract. Geotechnical engineering involves several disputes, which are often not phrased in an intelligible manner for non-specialists. As a result, they are mostly omitted or glossed over in instruction. In the same grey area belong broader questions related to how different soils, or civil engineering materials, are alike or different. When available, answers to such questions give confidence to inquisitive instructors and could help students connect previously disjointed pieces of knowledge. This article presents a set of disputed issues as questions, focusing mostly on topics concerning soft clays. Its goal is to guide geotechnical engineering instructors in addressing difficult questions confidently, mainly for their own benefit, rather than sidestepping them out of uncertainty.

1 Introduction

Have you ever felt that the doctor you consulted for a non-life-threatening health problem didn't really know what was causing it, yet still was comfortable discussing it and even prescribing treatment? The same is true of university professors who allow certain questions and answers to remain tacit on the grounds that making them explicit would confuse their students. At least a doctor might be excused for not having thought through a specific case before it materializes in the waiting room; a professor, however, cannot be excused for failing to think through difficult questions and commit to writing answers on the grounds that "no student will ever ask me this". Granted, professors cannot know everything—particularly at the introductory level, where topics are broader and thus more distant from current research, especially that of younger faculty. In such cases, effective collaboration between education and thematic committees can be essential to achieving meaningful impact.

This article contributes a set of questions, indicated in italics, which offer opportunities to elaborate on soil mechanics concepts and focus mostly on issues concerning soft clays. While the answers are not straightforward to at least the second author, they may also prove demanding for others. Questions are of three kinds. The questions relevant to soft clays are answered from the expert point of view of the first author. For the remaining questions, the authors offer either tentative answers or their best educated guesses. In all cases, the ultimate goal is to invite engagement from the wider geotechnical engineering community and stimulate further work.

There could be no better opportunity to present this work than a conference on soft soil engineering, organized by a technical committee known as "Soft Soils". For the non-expert, a broad and already challenging question naturally arises:

> *Why a special conference or committee on soft soils?*

This is then followed by more specific questions.

> *Granted, soft soils deform more – but does this require fundamentally different soil mechanics?*
> *Do the magnitude and the time dependence of deformation require a distinct approach, and if so, in what fundamental ways does it differ from conventional ones?*

This article is intended as a pilot for geotechnical engineering instructors, demonstrating how challenging questions can be approached systematically –or at the very least be acknowledged– instead of being avoided due to uncertainty. The article concerns the conceptual understandings of engineering instructors, a topic so far unacknowledged in the literature on engineering education, and it rests on the assumption that these understandings exhibit variation [1]. This variation may be hidden when instructors teach the same procedures but hold different beliefs about teaching (e.g., the attitude "I don't want to confuse my students" will veil the instructor's true beliefs on concepts) and soil mechanics (for an example, see Section 3.1.1). The article is equally addressed to practitioners who, unlike the doctor in the introduction, would welcome the opportunity to think about a soil mechanics issue that has not been central to their past projects.

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2 Guiding context

In this section, the second author presents the ideas that helped shape her thoughts and convinced her that the task of elaborating in writing on conceptual understanding is important and useful. In 1990, Ernest Boyer, at the time president of The Carnegie Foundation for the Advancement of Teaching, published the influential report *Scholarship Reconsidered: Priorities of the Professoriate* [2]. The report challenged the then current views of faculty priorities and the true meaning of scholarship. Boyer [2] distinguishes four kinds of scholarship: discovery, integration, application, and teaching. The scholarship of discovery comes closest to what is meant when academics speak of research. The scholarship of integration is carried out by scholars who give meaning to isolated facts, putting them in perspective. The first two kinds of scholarship, discovery and integration of knowledge, reflect the investigative and synthesizing traditions of academic life. The scholarship of application is carried out by the scholar who asks, "Can social problems themselves define an agenda for scholarly investigation?". Finally, the scholarship of teaching both educates and entices future scholars. Teaching, at its best, means not only transmitting knowledge, but transforming and extending it as well. What Boyer did not stress is that teaching provides incentives for synthesis work far more often than research does.

Synthesis is a necessity every time we attempt to answer in writing broad or fundamental questions, or we discover disjointed underlying assumptions of calculation procedures routinely taught in introductory soil mechanics courses. These answers are not needed for problem solution per se (this is exactly the reason or the excuse for instructors not mentioning them in teaching), but they will guide the decisions made before we start solving a problem (e.g., see Section 3.1.1). It is crucial we are aware of assumptions we take for granted –to the point they have become beliefs– when we attempt to use the same procedure for a seemingly similar problem, for which the underlying assumptions may not hold. Therefore, assumptions and beliefs better be written rather than remain tacit. Herein, we attempted to phrase questions that shed light on underlying assumptions concerning some fundamental topics in soil mechanics. In order to invite discussion, the questions have to be brief and targeted. To this end, most questions are phrased as a choice between options (A) and (B). As already mentioned, conceptual understandings are not binary (right-wrong), i.e., there is not a single meaningful conceptual understanding. On the contrary, there exists a cluster of valid, transferable conceptual understandings [1], i.e., understandings that can be productively used to reason, transfer knowledge, connect pieces of knowledge, or create new knowledge. To this end, the questions are phrased as follows: “Is it more appropriate to think of X as (A) or (B)”?

3 The questions

3.1 Disputed issues: unavoidable questions

Geotechnical engineering has several disputes, which are often not phrased in an intelligible manner for non-specialists. As a result, non-specialist instructors might not be aware of the dispute, let alone feel comfortable addressing it in instruction. Several of these disputes concern central issues in geotechnical engineering and are often related to clays. Examples include: shear strength, cohesion, stability of unsupported vertical clay cuts, consolidation, and secondary compression. This article, after starting with a question on shear strength to set the stage, focuses on the compression of soft clays, with an emphasis on the assumptions underlying the procedures used to calculate consolidation settlement and secondary compression.

3.1.1 A most fundamental question on shear strength

Ledesma [3] has dedicated an entire article to disputed issues concerning shear strength, noting how surprising it is that such a central issue to geotechnical engineering has attracted so little discussion. Herein, we switch the focus from what instructors choose to teach about the shear strength of clays to what instructors themselves believe, with the aid of the question below.

Of the two shear stress parameters c' and φ', defined in axes of shear stress τ and effective normal stress σ', is it more appropriate to think that (A) the quantity c' corresponds to a mechanism resisting shear deformation that is characteristic of clays or (B) the quantity c' is simply a byproduct of the decision to model shear strength with a straight line?

Instructors who choose to remain quiet or non-committal will affect their students in ways they cannot predict. If they make their stance explicit, they have a better chance of influencing the outcome. This question will not be discussed further herein in hopes that TC306, the technical committee on geoengineering education, will use it to elicit answers with supporting evidence and perhaps stage a debate.

Note that the study of numerical questions selected for exams by the instructors, who might believe (A) or (B) or not want to commit, does not offer any clue to their beliefs and to what they might have said or failed to say in class. This is not to be interpreted to mean that deeper beliefs about concepts do not have a bearing on solving problems. As already mentioned, these beliefs will guide the decisions made before we start solving a problem and, therefore, they better be explicit rather than tacit. Making this particular belief about shear explicit will become relevant to a problem of unsupported vertical clay cuts [4]. A geotechnical engineer perceiving cohesion as a bonding of soil particles, specific to clays, will be more likely to see that this cohesion helps the clay cut stand permanently. On the contrary, a geotechnical engineer who has learned to think of clays and sands as more fundamentally the same than different will be more skeptical about the origin of the strength of the clay cut and will be more amenable to seeing it as a result of capillary forces, i.e., something temporary, affected by the relative amount of air and water in clay pores. Having given an example of a question as a "mind exercise" for instructors, this article will turn to two less momentous questions related to the settlement of clays.

3.1.2 Consolidation and secondary compression: sequential or not?

Kinslev [5] discussed teaching decisions concerning the secondary compression of clays, noting three very different approaches taken from three introductory soil mechanics textbooks: i) not mentioning secondary compression, ii) giving a formula to calculate secondary compression using the coefficient of secondary compression, and iii) stating that calculating secondary compression is not possible with introductory knowledge of soil mechanics. In his presentation, Kinslev [5] used the schematic shown in Figure 1 to depict two different approaches to describe secondary compression, which puzzled the second author and prompted the phrasing of the question below.

> *Is it more appropriate to think that (A) secondary compression follows consolidation, i.e., it commences after the dissipation of excess pore water pressures caused by loading, or (B) secondary compression commences before the dissipation of excess pore water pressures?*

A comprehensive answer can be introduced with the following brief statements:

> After primary compression ends, only secondary compression remains, which is why it can be uniquely defined at this point. However, secondary compression also occurs during consolidation (primary compression), which unfortunately makes it impossible to analyze the primary compression in isolation.

While the fundamental distinction between primary and secondary compression (and their respective physical mechanisms) may seem philosophical to many practitioners and students, it is, in fact, crucial to settlement prediction, as it affects the scaling from laboratory measurements to predictions at the field scale. This effect is particularly significant in soft soils where deformations are large. The interplay between primary and secondary compression became a famous dispute originally presented by Ladd et al. [6] as two cases: Creep hypotheses A and B. The two hypotheses concern the scaling from the laboratory to the field, and at the time they were first discussed [6], hypothesis A assumed sequential primary and secondary compression, while hypothesis B stated (and still states) that they can overlap. In the following decades, advocates of both hypotheses reached agreement about the existence of creep (secondary compression) during consolidation (primary). However, proponents of hypothesis A still argue for a constant strain at the end of primary compression regardless of the thickness of the clay layer, in other words, independent of consolidation time. Proponents of hypothesis B now further posit a unique relationship between effective stress, void ratio, and strain rate. This unique relationship was first introduced into the soil mechanics literature in 1957 by Šuklje [7] and is depicted by a set of curves, which are known as isotache curves because they correspond to the same strain rate in the effective stress – void ratio space. The Online Supplement [8] discusses the equivalence between isotache and isochronous curves, which relate stress, deformation, and time in the creep literature. The isotache approach is presented in detail by Leroueil [9] and further explained in [8] and [10]. In practical terms, each hypothesis predicts a different settlement in the field. As illustrated conceptually in Figure 1, for the thick sample, i.e., in the field, at any given time after construction, creep hypothesis B predicts larger strain and, thus, larger settlement than creep hypothesis A.

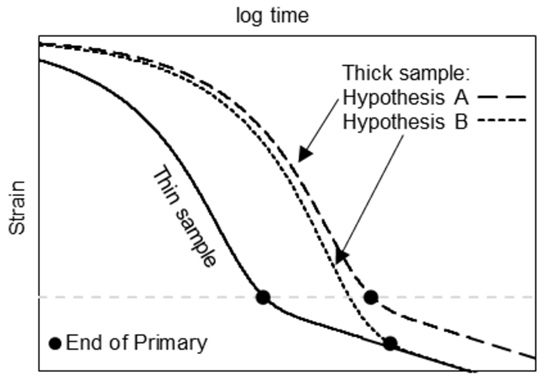

Fig. 1. The origin of hypotheses A and B for extrapolating from the laboratory (thin sample) to the field (thick sample), as proposed by Ladd et al. [6], modified from Degago et al. [10], e.g., to also include strain of the thick sample in the entire time interval.

Advocates for both creep hypotheses have been arguing their respective beliefs for nearly 50 years, e.g., [9-12]. Broadly speaking, advocates of hypothesis A present laboratory oedometer tests on samples with different heights and show that the End of Primary (EOP) void ratio is the same, e.g., [11], while advocates of hypothesis B compare laboratory oedometer tests with test embankments and find different void ratios for the same effective stress and associate this with the difference in consolidation time, e.g., [10]. The data presented by both groups are well-presented and convincing of their respective creep hypotheses, which makes it very difficult for those not closely related to the topic to take a stance.

In the opinion of the first author of this paper, the creep hypothesis dispute holds important meta knowledge by highlighting that even on a well-established topic like consolidation, we cannot just close the case as "solved" and use textbook methods without arguing our beliefs and presenting the evidence to support them.

3.1.3 Calculating 1-D consolidation with Terzaghi theory or not?

In the second author's interpretation, allowing for the possibility of secondary compression, i.e., a type of creep, to progress during primary consolidation invalidates Terzaghi's theory of one-dimensional consolidation. To this end, this section addresses questions related to using Terzaghi's theory to calculate settlements.

Is it more appropriate to think that preconsolidation pressure: (A) signifies the highest stress experienced by the soil in the past or (B) marks a change in behavior, i.e., delimits two ranges of stress-strain behavior?

Note that answer (A) is an interpretation of observations, whereas (B) is a description of observations. Hence (A) and (B) are not mutually exclusive, since (B) is broader than (A).

To the cognoscenti, this question may appear to concern mostly nomenclature. While the term "preconsolidation pressure" is still generally used in the presentation of compression of soil, the more accurate or general term "yield stress" is common among those working on the topic. The term "preconsolidation pressure", σ'_{pc}, was first introduced in 1936 by Casagrande [13] to exactly refer to a previous overburden stress that was later removed but is still reflected in the mechanical behavior of the soil. There is nothing wrong with this term per se; it can be thought of as a subset of the more general term "yield stress" or "vertical yield stress", σ'_{vy}, recommended by Burland [14], which makes no assumptions about the cause of the change in mechanical behavior. These terms are also reflected in the commonly used ratios with respect to the effective vertical stress before loading, σ'_{v0}: Overconsolidation Ratio (OCR), $\sigma'_{pc}/\sigma'_{v0}$, and Yield Stress Ratio (YSR), $\sigma'_{vy}/\sigma'_{v0}$, which refer to their respective counterpart terms for the stress point. Burland [14] advocates that the term "preconsolidation pressure" should be reserved only for when the existence of such pressure can be ascertained on the basis of geological evidence. Burland [15] further notes that "it is the norm rather than the exception that normally consolidated natural clays have values $\sigma'_{vy}/\sigma'_{v0}$ as high as 1.5".

In most textbooks, the concept of yielding in the e-logσ'_v plane (or a similar plane) is commonly presented as preconsolidation, perhaps due to its simplicity and ease of comparison to the oedometer test, where different preconsolidation pressures can be simulated by loading and unloading. The motivation for the more generally applicable term "yield stress" aligns with viewing the effects of secondary compression (i.e., creep) as an "apparent preconsolidation pressure" that has nothing to do with a previous overburden [9, 14, 15]. Similarly, aging effects other than creep, e.g., cementation, bond formation, and structure, may produce a yield behavior that is not associated with a previous overburden stress.

Considering all the exceptions to the 1-D consolidation theory by Terzaghi, the following questions again rise naturally:

Is it more appropriate to calculate final settlement for clays by (A) adding the consolidation settlement according to the Terzaghi theory and the secondary compression using the coefficient of secondary compression or (B) …? Does the practitioner have another option –i.e., is there an option (B)?– and, if yes, which one and in what fundamental ways (e.g., differences in underlying assumptions, i.e., not differences in procedural steps) does this option differ from Terzaghi's theory?

Following the answer to the question in Section 3.1.2, a more appropriate method for calculating final settlements for clays is found in the framework of isotaches (see Online Supplement). Herein lies no objection to the Terzaghi consolidation theory as such, only a realization that it does not explicitly consider how to scale to a field case. The Terzaghi consolidation theory can be thought of as a very good approximation of the general behavior of soil. In some cases, it may be enough to use this theory for settlement predictions, but in some cases, further complexity is required. In this regard it is useful to realize, that while creep hypothesis A may easily be applied in "hand calculations", hypothesis B requires incorporation into a numerical integration routine. Judging what is necessary is a task for the responsible engineer, who therefore needs to be aware of the extensions to Terzaghi's theory. As also discussed in connection with the question in Section 3.1.2, the dispute over how to go from laboratory to field scale is still not a closed case. The discussion in this paper and the Online Supplement [8] are addressed to those who want to attempt such scaling.

3.2 Broad issues: optional but useful

This section includes four questions that are not of first priority to address in geotechnical engineering courses, but they are useful for clarifying what "is" and what "is not" regarding creep. To the second author, at least, it is not clear how prevalent creep is for soils. These questions are more of the exploratory type, i.e., not phrased as alternatives (A) and (B), and the answers offered are tentative and brief.

Q1: *Is there something fundamental to creep that can help students unify different but related behaviors of materials? Or is creep an umbrella term for many different time-dependent processes of deformation of solid materials under unchanging loading situations? In other words, is it a concept that mostly unifies symptoms?*

Like in other materials, creep in soils is likely a combination of several mechanisms. There are many probable suggestions presented in the soil mechanics literature, but not yet a unifying principle, as far as the first author is aware. However, since creep is dominant in high plasticity clays and generally in high surface area granular materials, it is plausible that creep is related to particle interactions where bound surface water plays an important role.

Q2: *Is it educationally useful to invoke creep to explain/understand "secondary compression"?*

Creep is discussed for other civil engineering materials as continued deformation under constant load, which are the same conditions as when we see it in soil. Hence, the term creep helps unify conceptual behavior across disciplines. The first author also recognizes the advantage of using "secondary compression" when explaining a consolidation time-curve as it relates more directly to the term "primary compression" and thereby provides soil-specific context.

Q3: *Geotechnical engineering has one famous case study observed for centuries: the Tower of Pisa. Is this a case of creep? If not, what is the difference between the delayed deformation of the foundation soil of Pisa and "bona fide" soil creep?*

The main investigators involved in the stabilization of the tower of Pisa mention creep mostly when discussing the future of the tower [16]. They offer two scenarios, one optimistic and one pessimistic, stating that future scenarios "assume that the continuing increase of foundation inclination with time originated from the combined effects of the foundation soil creep and of the groundwater oscillation". The assumption for the optimistic scenario is that the dominant mechanism for the leaning of the tower through the centuries has been fluctuations of the groundwater level, which implies that under the pessimistic scenario, creep was and will be again important.

The tower of Pisa offers the opportunity to stress that "creep as a material property" should not be confused with "time-dependent response of a geotechnical system". This system-level response will be a compound outcome that may involve material creep, ongoing drainage and consolidation in layers that are still dissipating pore pressure, stress redistribution within the soil mass, and geometric or loading changes over time.

Q4: *What about potential slope stability problems related to old failure surfaces that are reactivated? Would we describe this slow movement of slopes as creep or not?*

We are lacking a proper definition of the micromechanics behind deformation behaviors that can explain all cases (one-dimensional settlement, slope failure, etc.). It is plausible that the mechanisms responsible for creep are related to slopes as well, but due to the different loading conditions, they may manifest differently. A triggering event that reactivates a failure surface will complicate matters even more.

4 Concluding remarks

In this paper, we phrased questions that help make explicit how instructors think about soil mechanics concepts, and we addressed at some depth the subset of questions concerning the compressibility of clays. Contemplating how to teach in an area with disputes offers to the instructor and the geotechnical community opportunities to think about the nature of the dispute in at least three useful ways. First, the focus shifts from the different elements to the common elements of the conflicting approaches, an example of which was the partial convergence of hypotheses A and B for secondary compression. Second, the presentation of the dispute in an intelligible manner to a non-expert brings more participants into the discussion, who may, in turn, bring a more objective appreciation of the key differences and even new perspectives. Third, the search for ways to present disputed issues will eventually lead to productive ways to present different theories in a common frame. For example, the theory of relativity did not prove that Newtonian physics is wrong. It helped illuminate its limits of validity for high speed, acceleration, and gravity, and showed that it is an excellent approximation for classical mechanics on Earth (and other planets) and classical celestial mechanics.

The importance of creep for soft clays offered the impetus to question the prevalence of creep-type problems in soils and seek connections with creep phenomena in other engineering materials. Whereas the literature on creep of these other materials does not shed light on the mechanisms of creep in soils, it was found to offer context to understand a calculation procedure used for soils. It is conceivable that if creep is presented as a rarity or a footnote in steel, concrete, and soil, civil engineering students will not be well prepared to anticipate creep effects when they are important. It may be useful to explicitly use the term creep when relevant phenomena are encountered in geotechnical engineering to raise awareness of their prevalence. Using exclusively specialty terms for each creep behavior, may mask a possible prevalence of creep and detract attention from the kinds of soil where it is mostly needed, soft soils.

When learning (or teaching) soil mechanics, it is natural to first deal with the most dominating or basic principles of soil behavior. This could take the form of, e.g., stiffness as a constant modulus (Elasticity theory), strength as a simple failure envelope (Mohr-Coulomb), and consolidation as simple pressure dissipation (Terzaghi consolidation). Despite their oversimplification, it may be argued that these concepts can still be used to predict soil behavior reasonably well. However, this may not be adequate in many scenarios; hence, greater complexity may be needed. Judging when such additional complexity is necessary largely involves understanding the assumptions underlying simple concepts and evaluating whether they are appropriate in a given scenario. It also requires knowledge of what the next level of complexity is and how to introduce it correctly in that same scenario.

In most high school physics exercises, students are instructed to ignore wind resistance (e.g., when solving equations for a falling or thrown body). Similarly, this paper illustrates the importance of making explicit what is ignored when teaching basic soil mechanics so that the students are made aware of the existence of a more complex reality without having to grasp everything at once.

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