Soils and Rocks
An International Journal of Geotechnical and Geoenvironmental Engineering
www.soilsandrocks.com
ISSN 1980-9743
ISSN-e 2675-5475

Helping students classify and frame capstone geotechnical design courses

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Case Study

Keywords
Teaching design
Complex problems
Framing
Classification

Abstract

Students often express an anxiety about how knowledge is classified (i.e., differentiated) and framed (i.e., prioritized, and sequenced) in capstone design problems. This anxiety is by design as capstone design courses are meant to test students' ability to solve complex problems that are weakly classified and framed. Nevertheless, educators can play a role in scaffolding student progress, so students advance past a conceptual understanding of problems to applying technical acumen learnt in prior years. This paper presents three geotechnical design projects set by the author, along with three interventions used to scaffold student progress. Projects included the design of an industrial waste facility for dry filtered residue, design of remedial works for a clay river embankment subject to undercutting, and design of a remining method for mine slimes contained behind a sand embankment. Interventions included requiring students to prepare, present and critique presentations based on weekly stage gates, collaboratively brainstorming, and ranking high level implications of a design, and collaboratively brainstorming specific implications of a design. When implementing such interventions care must be taken to ensure they remain student driven, or the learning benefits of a capstone design course may be lost.

1. Introduction

Engineering education strives to provide students with a skill set with which they can advise clients on the best way to tackle their problems. In civil engineering, problems faced are often the design of an engineering artefact, such as a dam, building, bridge, or road. Often these artefacts are bespoke, as they are non-prototypical, and this introduces significant uncertainties in the design process (Bulleit et al., 2015). These uncertainties can be summarized as ignorance, uncertainty and complexity (Elms, 1999). Ignorance pertains to a lack of designer knowledge, uncertainty relates to information the designer needs but does not have, and complexity captures the reality that it is difficult to predict the actual behavior of an artefact.

Engineering science has made significant strides to address complexity in predicting artefact behavior. Consequently, engineering education has increasingly focused on teaching engineering science to address ignorance (Bulleit et al., 2015). Nevertheless, particularly in geotechnical engineering, complexity remains and information available to implement elegant scientific methods is often limited. Capstone design courses are therefore advocated in engineering programs (Harris et al., 1994). These allow students to apply scientific methods they have learnt and to grapple with uncertainties inherent to the design process. Geotechnical design courses allow students to appreciate how theory is applied to practice, especially the shortcomings of theory, how to develop a good geotechnical model through coming to grips with obtaining soil parameters from field and laboratory tests (Atkinson, 2008; Poulos, 1998). Nevertheless, it must be kept in mind that design is not a skill that can be taught in its entirety in the classroom and there remains an obligation on employers to contribute to the continual education of their employees (Atkinson, 2008).

Two difficulties in presenting design courses are the choice of project and the pedagogical approach. Projects set ideally need to meet all the attributes of a complex problems as set out in the Washington Accord (IEA, 2015):

- Depth of knowledge required: Cannot be resolved without in-depth engineering knowledge (…) allows a fundamentals-based, first principles analytical approach;
- Range of conflicting requirements: Involve wide-ranging or conflicting technical, engineering, and other issues;

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Submitted on September 1, 2023; Final Acceptance on December 20, 2023; Discussion open until August 31, 2024.

https://doi.org/10.28927/SR.2024.009623

- Depth of analysis required: Have no obvious solution and require abstract thinking and originality in analysis to formulate suitable models;
- Familiarity of issues: Involve infrequently encountered issues;
- Extent of applicable codes: Outside problems encompassed by standards and codes of practice for professional engineering;
- Extent of stakeholder involvement and needs: Involve diverse groups of stakeholders with widely varying needs;
- Interdependence: High level problems including many component parts or sub-problems.

Phang et al. (2018) show how difficult it is to set problems that meet all these criteria. However, complexity and uncertainty involved in geotechnical problems (Cardoso, 2015) often means they can meet the complex problem attributes listed above. Very few geotechnical engineering problems have been codified, and codes and standards that are available largely dictate the level of safety that should be achieved rather than the design steps to be followed. Nevertheless, careful consideration is required to meet the above attributes taking into account what students know or can figure out from resources available to them. If problems are too complex, student solutions can remain conceptual and not test students' ability to apply technical acumen.

Closely connected to the choice of design project is the pedagogical approach taken. Wolmarans (2013) recommends the following two fundamental analytical concepts of Bernstein (2000) as a useful framework for the pedagogical approach in design courses: classification (i.e., the extent to which one type of knowledge is separated from others) and framing (i.e., deciding what knowledge to apply and when). Design courses earlier on in a degree program need to have strong classification (i.e., limited to one domain of knowledge) and lecturers need to provide strong framing (i.e., projects are sequenced so that specific pieces of knowledge are applied stepwise). However, as students build a more diverse knowledge design courses should tackle problems with weak classification (i.e., in multiple domains) and weak framing (i.e., students should become responsible for deciding what knowledge to apply and when). This case study presents various interventions developed to scaffold student progress as they undertook weakly classified and framed capstone projects.

2. Capstone design course at Stellenbosch University in South Africa

Students at Stellenbosch University complete a capstone design course in the last semester of the final year of their 4-year Bachelor of Civil Engineering degree. Students are divided into cohorts and undertake design in either structural, pavement, geotechnical, hydraulic, or coastal engineering. Design projects need to be based on real world projects and therefore instructors are either full-time staff members with industry experience or ad hoc appointees from industry. Although centered in single domains, projects must still be weakly classified and require interacting with other knowledge domains for completion. As projects need to involve various stakeholders, instructors (or guest lecturers) take on various roles during the course. For instance, instructors take on the role of client, setting deliverables for students to achieve. Roles extend to parties providing information for students to consider in the design (e.g., environmental specialists, site investigation practitioners, regulators, surveyors, and contractors). Finally, instructors need to be teachers, scaffolding student progress as problems are unfamiliar and do not have closed form solutions commonly encountered in earlier engineering science courses.

The design course is divided into two stages; a five-week conceptual design stage followed by an eight-week detailed design stage. In the conceptual stage, students work in groups to come up with various solutions to the problem. Solutions require ranking conflicting requirements to propose a preferred option. Typically, the amount of information provided at this stage is limited and students are expected to apply depth of analysis that extends past learnt engineering science. Students are then required to propose what additional information they would require when developing the solution further. Table 1 details the various conceptual design problems set by the author for geotechnical designs. The final deliverable at the end of the conceptual design stage is a group report. Groups also complete a buddy ranking exercise to proportion the group mark to individuals.

For the detailed design stage, students work individually to develop the design by applying engineering science. At this stage the scope is reduced, and students are provided with additional information. The reduction in scope is usually presented as a decision by the client to highlight that stakeholders that are not the design engineer can influence the direction of a project. However, this reduction still provides room for students to come up with different variations. The depth of analysis shifts from abstract concepts to applying technical acumen. Interaction between different components or phenomena must be considered in carrying out calculations to ensure proposed solutions are safe. Table 2 outlines the various detail design problems set by the author for geotechnical designs.

3. Conceptual design stage

3.1 Interventions

During the year in which the "Design of an industrial waste facility for dry filtered residue" was undertaken, two targeted interventions were trialed during the conceptual design stage to inform future practices. The first was an intuitive design exercise on the first day of class and the second was a series of weekly group presentations.

On the first day of class, following a brief presentation (23 slides) introducing the class to industrial waste, the conceptual design brief was distributed to the class along with a paper-based intuitive design exercise. This three A4-page paper-based intuitive design exercise outlined six (6) tasks, see Table 3, and provided space for notes and sketches to be made in response. No time limit was set for the exercise, but students took on average 1-hour to finish. Responses were assessed to determine whether students had a well-formed idea of the solution prior to the commencement of the conceptual design stage, and whether this improved in the final conceptual design report. Students were also asked to rate (1 to 10) their confidence in completing the conceptual design and state reasons for their confidence (or lack thereof).

To gauge and shape progress during the conceptual design stage, the second intervention required students to prepare weekly slide presentations based on stage gates (i.e., defined decision points where project progress was evaluated according to specified criteria). This helped students to sequence their work, but still required them to classify and decide what knowledge was important. During class sessions, two to three randomly selected groups presented their slides and fielded questions from the rest of the class. This was anticipated to be largely student driven to prevent the lecturer 'giving away' or framing the solution. Presentations also exposed students to real world industry practices wherein engineers need to provide regular updates to clients on design progress.

Table 1. Details of various conceptual design problems set.

Project:	Design of an industrial waste facility for dry filtered residue.	Design of remedial works for a clay river embankment subject to undercutting.	Design of a remining method for mine slimes contained behind a sand embankment.
Deliverables: (Not stated categorically but as a narrative in the brief)	1. Site selection 2. Deposition 3. methodology 4. Airspace model 5. Lining system 6. Information required to advance design	1. Geotechnical model 2. Slope stability analysis 3. Various remedial measures 4. Trade-off between remedial measures 5. Site investigation proposal	1. Geotechnical model 2. Cross section 3. Various remining methods 4. Trade-off between remining methods 5. Site investigation proposal
Information provided:	1. 1-page brief 2. Map of area 3. Photographs and notes from site visit 4. Grading curves 5. Atterberg limits 6. Moisture density relationships (Standard Proctor and Modified Proctor)	1. 1-page brief 2. Topographical map of area 3. One borehole log 4. Atterberg limits with depth 5. Natural water contents with depth 6. Post failure survey	1. 1-page brief 2. Grading curves for sand and slimes 3. Atterberg limits for sand and slimes 4. Moisture density relationships for sand (Standard Proctor) 5. Survey with cross-sections

Table 2. Summary of different detail design problems set by the author.

Project:	Design of an industrial waste facility for dry filtered residue.	Design of remedial works for a clay river embankment subject to undercutting.	Design of a remining method for mine slimes contained behind a sand embankment.
Deliverables: (Not stated categorically but as a narrative in the brief)	1. Updated geotechnical model 2. Depositional methodology 3. Design of liner system 4. Stability analysis 5. Capital and operational costs 6. Drawings	1. Updated geotechnical model 2. Update of slope stability analysis 3. Design of gravity retaining structure 4. Consideration of construction methodology 5. Cost estimate	1. Updated geotechnical model 2. Two-option trade-off 3. Design of chosen option considering: a. Seepage b. modelling c. Stability modelling
Information provided:	1. 1-page brief 2. Client decision on site 3. Letter report on site investigation 4. Letter report on field compaction and Guelph permeameter testing 5. Direct shear box testing on residue 6. Large shear box tests results for different liner interfaces 7. Sections of legislation 8. Airspace model and cross-sections 9. Rates list	1. 1-page brief 2. Client decision favouring gravity retaining structure 3. Layout of site investigation 4. 2 borehole logs 5. 2 unconsolidated undrained triaxial test result sets 6. 4 consolidated drained triaxial tests 7. 4 cone penetration tests 8. Rates list	1. 1-page brief 2. Client decision favouring two solutions 3. 1 borehole log through sand embankment 4. 3 cone penetration tests within the slimes 5. 3 direct shear box tests on sand 6. Constant head permeability test on sand 7. Falling head permeability on slimes

Table 3. Intuitive design exercise.

Task	Description
1	By listing positive and negative aspects for Site A and Site B, decide which site is best suited for the waste facility.
2	Calculate the airspace (i.e., volume) required for the waste facility over the facility life, then propose and illustrate a stable mound (dimensioned) sketch.
3	Suggest suitable equipment to handle the material and build up the waste facility. Estimate how many truck trips will be required each day.
4	Suggest a number of methods to prevent ground water contamination and discuss how each would impact the safety and cost of the waste facility.
5	What factors are most likely to influence the design?
6	What additional information do you require to complete the design?

Table 4. Conceptual design evaluation form.

Questions and statements	Response type
Was the conceptual design 'given away'?	
During class the lecturer did not give away the conceptual design.	Likert
The lecturer easily gave away the conceptual design solution during class.	Likert
Was the conceptual design challenging?	
The conceptual design was very challenging.	Likert
As a student I found the conceptual design very easy to carry out.	Likert
Were the conceptual design submission requirements clear?	
The conceptual design submission requirements were confusing.	Likert
I did not know what to produce for the conceptual design submission.	Likert
The lecturer made it clear what was required for the conceptual design.	Likert
I understood what was required for the conceptual design submission.	Likert
Opinions of students	
Which one (1) aspect was most helpful about the course?	Open
Which one (1) aspect was most annoying about the course?	Open

Following the submission of the conceptual design report, students were asked to complete a feedback form to evaluate the interventions (see Table 4). This consisted of eight statements that students evaluated using a Likert scale (Strongly agree, Agree, Neutral, Disagree and Strongly disagree). These statements were set to evaluate whether the lecturer 'gave away' the solution, how difficult students found the project and whether submission requirements were clear. Two open-ended questions asked students to list helpful and annoying aspects of the course.

3.1.1 Confidence in completing design after intuitive design exercise

On average, students stated a confidence level of 5/10 to complete the design successfully, although this ranged from 1/10 to 10/10. Stated confidence levels had no correlation to performance at any stage of the design project. When reviewing reasons for stated confidence it became apparent that most responses could be divided into two groups, students either raised reservations regarding their knowledge of the subject or deficiencies in provided information.

Sixteen (16) of the twenty-five (25) students (i.e., 64%) highlighted an uncertainty of the subject as a reason for their lack of confidence[1]. Three (3) students (i.e., 12%) suggested that their lack of confidence was due to a lack of information. Four (4) students (i.e., 16%) highlighted both uncertainty and insufficient information as obstacles to completing the design project. Students that highlighted uncertainty of the subject also stated that this could be overcome by revising previous work, engaging with the lecturer and fellow students, or searching through library and internet resources. These results highlight the importance of lecturers scaffolding students through a design project as they are weakly classified and framed. Lecturers need to think carefully about how to remind students of material covered in previous courses and make sure that it can be applied in capstone design courses.

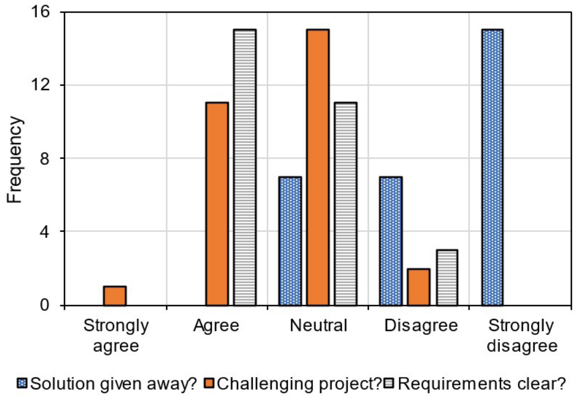

Figure 1. Histogram summarizing student feedback.

3.1.2 Performance in intuitive design exercise relative to final conceptual design marks

On average students scored 55% for the intuitive design exercise. This average improved to 74% for the final conceptual design submission. However, there was no correlation between student marks for the two activities (Pearson correlation coefficient, $r = 0.04$). The increase in marks suggests that the students' understanding of the design improved because of the tasks undertaken during the conceptual design stage. This intuitive design exercise was not used in subsequent years.

3.1.3 Post conceptual design student feedback

Figure 1 plots the aggregated Likert responses per feedback question (see Table 4). Twenty-nine (29) students completed the evaluation. This shows that most students felt that the lecturer did not 'give away' the solution, which means they felt they had to discover it themselves. Most students were neutral on whether the project was challenging, although a larger group felt it was difficult compared to those who did not. Most students felt that requirements were clear, however, a large group were neutral on this aspect.

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[1] The total class size was 30. Five students were absent on the day of the survey.

Twenty-five (25) of the students (i.e., 86%) found the weekly progress presentations to be the most helpful aspect of the conceptual design. Verbatim quotes below highlight reasons why students found these sessions helpful:

- "Weekly presentations helped to observe other group's ideas and to critic [sic] each other. Keeps one up to date with each section of conceptual design";
- "The interactive class presentations. Students learned to speak in front of the class and interact with other student[s]";
- "The fact that we were a task for each week, it minimize[ed] the confusion that could have happened if we were given all the task in a goal";
- "Lecturer sessions and feedback from the class, the sessions assisted in clarifying most concepts that were initially unclear and validated most mistakes".

These quotes highlight how the presentations enabled students to sequence their work and figure out what knowledge was important. The positive response to this intervention, and the comments received helped to validate progress presentations as a means to gauge and shape progress at the conceptual design stage. This intervention was therefore implemented in subsequent years.

Categorizing responses to annoying aspects was challenging. However, a common theme was a lack of or an uncertainty about how to apply knowledge they had learnt to solving the problem and information overload. For instance, common phrases included, "amount of information", "number of unknowns", "vaguely", "deciding which assumptions needed to be made", "lack of information", "atmosphere of uncertainty", "not much information known", "need more guidance", "vagueness of some the topics", "no clear instruction on what is right/wrong" and "not enough background". Some students also struggled with understanding the distinction between concept and detail design. Poor group dynamics was also raised by a few students. This feedback again highlighted the need to help students frame and classify the project so they can see how content they have already learnt can be applied.

4. Detail design stage

4.1 Intervention

During the year in which the "Design of a remining method for mine slimes contained behind a sand embankment" was undertaken, two targeted interventions were undertaken during the detail design stage to inform future practices. These interventions were collaborative learning exercises designed to help students develop guiding documents to tackle the detail design stage. Remining the slimes required flooding the slimes compartment so that a barge could be used to recover the slimes. This water would result in a phreatic surface developing within the sand embankment (also referred to as a wall). The detailed design stage required students to evaluate geotechnical implications of either remining slimes up to the sand embankment or leaving at least 4 m of slimes against the sand embankment. Students had to then design measures to prevent the sand embankment from failing.

The first intervention was a planning session during which students brainstormed geotechnical implications to consider in the design. This session was hosted online using a video conference platform (Microsoft Teams). At the start of the session a link to a shared file (Microsoft Word) was distributed to all students. Students were then separated into ten (10) random online breakout groups (3 to 4 students as the class size was 35). In these groups, students populated the shared document with bullet points on geotechnical implications of design options, parameters required to assess these concerns, and the analysis that would need to be performed. A time limit of 45 minutes was set for this exercise, during which the lecturer visited – virtually – each breakout group to assess progress. The shared document was left available for 24 hours and then taken down. These statements were then copied into an online survey and ranked by students using the following criteria a week later:

- Irrelevant to the problem: Score = 1
- Minor point and poorly developed: Score = 2
- Minor point and well developed: Score = 3
- Major point but poorly developed: Score = 4
- Major point and well developed: Score = 5

This ranking was undertaken to sperate statements based on relevance. The ranked statements were then distributed to students as a Planning Document.

The second session (held a week after the ranking exercise, by which time students had become more familiar with information provided) used the same digital crowdsourcing approach but focused on parameters, analysis, and sources of knowledge. In similar breakout groups students populated two shared tables, one for the embankment material and the other for slimes material, with the following:

- Parameter/Information
- What test is used to determine the parameter/information?
- Where in the textbook[2] can you find relevant information?
- How do the values vary?
- What is the significance of this variation?
- Why do you need this parameter/information?

These questions were designed to help students classify knowledge needed and to frame the way knowledge would be applied. Students had 45 minutes to complete the exercise. They were not allowed to delete anything already added but could highlight and comment on points they were unsure about. The lecturer was also able to monitor progress and insert comments. At the end of the session the document was saved in portable document format (i.e., PDF) and distributed to the class. This was termed the Geotechnical Model Guiding Document.

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[2] Knappet & Craig (2012).

To evaluate the utility of the collaborative learning exercises students completed an online survey. Table 5 details the questions asked, responses students could select to answer the questions, and the proportion of students selecting each response. Twenty-seven (27) students completed the evaluation.

4.2 Evaluation

4.2.1 Collaborative learning documents produced

Table 6 reproduces the top two ranked statements and the bottom ranked statement for each of the planning questions posed to the class. A total of 118 statements were proposed by the students. The student driven ranking exercise was efficient at separating relevant and irrelevant statements and no intervention by the lecturer was necessary. Table 7 reproduces two rows with responses regarding the geotechnical model for the sand embankment and slimes material respectively. For the embankment material five (5) rows were developed covering: permeability, phreatic surface, drained strength parameters, unit weights and relative density. For slimes material ten (10) rows were developed covering: cone tip resistance, permeability, effective stresses, undrained shear strength, phreatic surface, stability criteria, overconsolidation ratio, cone calibration factor (N_{kt}), pore pressure parameter (B_q) and drained strengths.

Table 5. Evaluation of collaborative learning exercises.

Questions	Potential responses	Frequency
How would you rate you understanding of the project before the collaborative learning exercises?	I had no idea what to do.	7 (26%)
	I had a vague idea of what to do.	13 (48%)
	I had a good idea of what to do.	5 (19%)
	I knew what to do.	2 (7%)
	I knew exactly what to do.	0
How effective were the collaborative learning exercises in guiding you?	The exercises were vital in guiding me.	4 (15%)
	The exercises helped to fill in blanks.	15 (56%)
	The exercises helped clarify concerns.	3 (11%)
	The exercises showed me a few extra things I needed to consider.	5 (19%)
	The exercises were a waste of time.	0
How often did you use collaborative exercises documents when working on the project?	I did not download them.	0
	I downloaded them but did not use them.	0
	I used them a few times.	12 (44%)
	I used them often.	12 (44%)
	I used them every time I worked on the project.	3 (11%)

Table 6. Examples of ranked planning document statements (statements are verbatim and retain imprecise terminology used by students).

Score	Statement
	What are the geotechnical implications of the two proposed re-mining options? Option 1: Re-mining slimes right up to the embankment.
4.5	Phreatic surface might be raised due to addition of water required for freeboard.
4.2	Saturation of the wall material due to the increased phreatic surface.
⋮	⋮
1.5	Larger water usage area.
	What are the geotechnical implications of the two proposed re-mining options? Option 2: Keeping a minimum of 4 m slimes against the embankment.
4.7	From the falling head permeability test, the times between readings is higher than those from the constant permeability test. This shows that the slimes are less permeable than the sandy material making up the embankment. Hence during construction when the dam is full of water, there is a lower risk of seepage occurring through the embankment wall when compared to option 1.
4.1	The slimes will reduce the infiltration and slow drainage through the wall as they are fine and have a lower permeability.
⋮	⋮
2.2	Barge floating equipment may experience space/movement restrictions as there is less room to operate within the basin.
	What parameters will you need for your geotechnical model? Embankment material
4.6	The drained parameters (internal friction angle) from the 3 shear box tests, and 1 SPT test on the embankment material. The SPT results can be interpreted by Ch 7.2 in the textbook.
4.5	The permeability of the wall, k, determined from the constant head (CH) permeability test on the embankment material.
⋮	⋮
2.0	Single borehole.
	What parameters will you need for your geotechnical model? Slimes material
4.5	The permeability of the slimes, k, determined from the falling head (FH) test on the slimes material.
4.3	The undrained strength parameter, cu, obtained from the 3 CPT tests on the slimes material. This can be interpreted by Ch. 7.5, 8th edition, which discusses the CPT analysis.
⋮	⋮
2.3	Elasto-plastic soil behaviour.
	What geotechnical analysis will you need to carry out?
4.6	Slope stability analysis & determination of safety factor - Section 12.3 in textbook; During operation safety checks for a *SF* of 1.3, post-operation safety checks for a *SF* of 1.5 (long-term stability).
4.3	Seepage: use flow nets through embankment dams (Section 2.9 in textbook, 8th edition) and filter design (Section 2.10, 8th edition) and transfer conditions (Section 2.8 in textbook, 8th edition).
⋮	⋮
2.0	Tunnelling works.

Table 7. Examples of geotechnical model statements (statements are verbatim and retain imprecise terminology used by students).

Item	Embankment material	Slimes material
Parameter/Information	Drained strength parameters (shear strength s, and internal friction angle)	k
What tests is used to determine the parameter/information?	Direct shear box test (select most appropriate result from the 3 DSB tests, namely the test with the most representative density) SPT test- find density which is most representative to use for DSB test	Falling head permeability test
Where in the textbook can you find relevant information?	Ch 5.4 (8th edition) Ch 5.5 (8th edition) - example 5.1 Ch 7.2 (8th ed) - SPT	Chapter 2.2, 2.8 and 2.9 (8th edition)
How do the values vary?	Phi angle and c' value increases slightly with depth, as normal and peak stress increases. From the three different DSB tests performed on the soil, it is clear that soil with a lower dry density that is less compacted, will have a lower peak shear strength and a greater internal friction angle. Test 1 indicates a loose silty sand, which is cohesionless and has an internal friction angle of 0.	3.7E-7 < k < 6E-7 on average k = 4.7E-7
What is the significance of this variation?	Lower part of wall has a higher shear strength than top part of the wall, as saturation increases downwards in the wall.	Variation is little in the data thus not that significant. Values fall in the range of low permeability.
Why do you need this parameter/information?	To determine a critical shear strength failure to design for, you would need to know where in the wall this value would occur. It is best to design for the worst-case scenario, which is represented in the first sample in the borehole logs at 6 m from the crest of the wall. To use drained strength parameters for slope stability analysis.	The permeability, k, will be needed to construct flow nets through the embankment (Ch 2.9) and determine transfer conditions (Ch 2.8).

While some statements contained errors and imprecise terminology it was generally not necessary to intervene as students had identified correct textbook sections to consult. An example of an intervention was where particle specific gravity (*SG*) was discussed. The following details the written exchange between lecturer and student:

- Student: [*SG*] Determines stability of slope and whether it will fail;
- Lecturer: I am not sure *SG* will determine if the slope fails;
- Student: Would *SG* not be used in the determination of slope stability? – Isn't the weight of the soil in the 'failure zone' required?;
- Lecturer: I guess in that sense.

4.2.2 Perceived usefulness of collaborative learning documents

Table 5 shows that prior to the collaborative learning exercises a large group of students had a very poor understanding (no idea to vague idea) of what to do for the detail design. Most students ranked the documents as useful guides (vital to fill in gaps), and more than half used them regularly (often to every time) when working on the design. This feedback confirmed the utility of the collaborative exercises. These exercises were performed when in-person interactions were not permitted due to COVID restrictions. Nevertheless, in an in-person setting students can still be divided into groups and can populate a shared document on laptops in a classroom or computers in a laboratory. Due to rotation of teaching duties the author has not had a chance to run the exercises with an in-person class.

5. Conclusions

Design is introduced at various stages during an undergraduate program in engineering. Initially, design is introduced with strong classification (i.e., limited domain of knowledge) and with strong framing (i.e., sequenced steps). Later in the program, typically in a capstone design course, the design is presented with weak classification (i.e., requiring knowledge from different domains) and with weak framing (i.e., students are responsible for determining what knowledge is relevant and when to apply it). Projects set must also meet the attributes of a complex problem if programs are aligned with the Washington Accord.

Surveys undertaken amongst students showed anxiety about the uncertainty that results from undertaking projects with weak classification and framing. This paper presented three interventions introduced to help students classify and frame the work required to solve design problems (with minimal lecture intervention):

- Preparing and presenting weekly presentation for critique by the rest of the class: Presentations were prepared according to stage gates (i.e., providing some assistance in sequencing work) but students were still required to classify and prioritize knowledge. Student driven critique was in most cases sufficient to frame what work was required;
- Poorly structured collaborative brainstorming activity followed by ranking: Students in small groups populated a shared document with statements in response to high level questions regarding implications of a proposed design. These statements helped students classify what knowledge was required,

but a student driven ranking exercise was required to frame these (i.e., decide what was important);

- Structured collaborative brainstorming activity: Students in small groups populated a shared document with statements in response to specific questions regarding the geotechnical model (an important sub-component) for the proposed designs. These questions spoke to the how (i.e., framing of analysis) of the problem and not the what (i.e., the solution). Students remained responsible for coming up with unique solutions of their own.

As students evaluated these interventions as useful to their studies, other educators may wish to implement these in their own courses. However, care must be taken so that educators do not intervene to the extent that students are no longer learning to stand on their own feet. Too much intervention can turn a weakly classified and framed project into a strongly classified and framed project. This then defeats the point of a capstone design project.

Acknowledgements

Without encouragement from Professor Kátia Vanessa Bicalho (Federal University of Espírito Santo) this paper would have remained on a dusty shelf.

Declaration of interest

The author has no conflicts of interest to declare.

Data availability

Design projects outlined in this paper are available from the corresponding author upon request. Raw student feedback is not available for confidentiality reasons.

List of symbols and abbreviations

c'	Effective cohesion
k	Hydraulic conductivity
PDF	Portable digital format
r	Pearson correlation coefficient
B_q	Pore pressure coefficient
N_{kt}	Cone calibration factor
CH	Constant head
CPT	Cone penetration test
DSB	Direct shear box
FH	Falling head
SF	Factor of Safety
SG	Particle specific gravity
SPT	Standard penetration test

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