Preliminary Development and Assessment of Engineering Judgment through Mixed-Reality Game-Based Learning

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Abstract— **Geotechnical engineers work with a complex material. Unlike steel or concrete, soil is heterogeneous, and its properties are difficult to predict. As such, judgment plays a significant role in geotechnical engineering practice and the design process is unavoidably iterative. This WIP starts with geotechnical engineering as the origin for defining engineering judgment, but the emerging theory can service all engineering decision making. The process through which aspiring engineers practice engineering judgment in their education remains a research area in its adolescence. Members of industry posit that experience is essential for competent engineering practice, but traditional engineering education practices provide few opportunities to acquire such experience. The *GeoExplorer* project is a mixed reality "mock internship" that allows students to get preliminary experience with field testing through a mixed-reality game-based learning environment. The CPT module of *GeoExplorer* was designed to both develop and measure gains in engineering judgment. The importance of defining engineering judgment with respect to engineering education standards became clear when designing this module to serve undergraduate engineering classrooms.**

Keywords—engineering judgment, theoretical frameworks, student development, critical thinking, professional engineer

I. Introduction

The response of engineering education to Generation Z students in (post-)pandemic times has accelerated the need for activities and assessments for undergraduate students to practice and improve their engineering judgment. Scholars in geotechnical engineering have preached about the importance of engineering judgment for decades, yet even with this implicit consensus, the academia lacks the appropriate tools. Beyond geotechnical engineering, all engineering educators feel mounting pressure to assess engineering judgment as they work with the current Engineering Program Criteria for Student Outcomes and Curriculum for implementation in the 2019-2020 ABET cycle [1]. Among others, the Student Outcomes require documentation for, "4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts," and "6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions" [1]. While engineering educators in higher education are expected to include ways of thinking, such as engineering judgment, in their curricula, to date there is no agreement on a formal definition of engineering judgment and the academic community has little to no guidance on the topic. Philosopher Michael Davis argues that "teachers of engineering… might do a better job if they were clearer about what the judgment they teach is and how it can be taught," and acknowledges that "so little has been written about judgment that [he] must leave many important questions unanswered—and some not even asked," [2], [3]. Other researchers and practitioners have proposed some answers to both the explicit (per Michael Davis) and implicit questions around engineering judgment and we present some of their musings in the literature review that follows.

The 2019-2020 adoption of the new ABET criteria is a manifestation of a paradigm shift in engineering practice. For example, it is necessary for all engineers to employ good engineering judgment in the so-called "Information Age" to appropriately constrain software inputs, analyze outputs, and contextualize the solutions [4]. For civil engineers particularly, the identification of the newest geologic Anthropocene time period has also amplified the complexity and frequency of the engineering challenges. As climate change and socioeconomic issues become increasingly prominent, it is not enough to judge if a design will fail; rather, a systematic and conscientious approach to the built environment is necessary [2].

However, within this context, undergraduate education continues to focus largely on theoretical calculations and not how one might apply these theories in their careers as engineers. Some institutions, departments, and individual instructors have made strides to address this by including more project-based work or design problems in their curricula, but these are difficult to meaningfully assess with respect to engineering judgment. An example of an engineering educator working to bring engineering judgment into the classroom is Dr. William Lawson of Texas Tech University who found that a "survey of engineering faculty shows they 'strongly' agree that engineer[ing] judgment is important for problem-solving, but most struggle to 'name specific things students can do to obtain judgment'" [5]. Another educator, Jonathan Weedon, performed a case study with a group of students tasked with solving a design problem to observe how they practice engineering judgment. Weedon argues that "while a definition of engineering judgment remains elusive, there is consensus among philosophers and theorists that engineering judgment is the product of experience in an authentic engineering environment, which a classroom is unable to replicate" and determines "that the practice of engineering judgment relies on displays [i.e., visual representations] to recognize and construct rhetorical tactics to satisfy the requirements of [an engineering] task" [6].

As more educators continue to grapple with the need to assess engineering judgment, educational video games and mixed reality or virtual reality learning platforms provide an important educational design opportunity. For example, some virtual gaming spaces for learning have focused on "sense-making" as a way to isolate and identify how students make decisions during gameplay in order to assess their learning gains [7]. The open-ended nature and opportunity for immediate visual feedback of educational video games lends itself to engineering education in a way that may improve the ability of instructors to both teach and assess learning gains for engineering judgment specifically [8]. To this end, in *GeoExplorer*, students navigate a simulated field experiment and gain "experience" with subsurface investigation [2]. The "sense-making" is then developed and measured to demonstrate that students have similar learning gains by engaging with virtual images as with real ones; therefore the experience students gain in a virtual engineering environment may be analogous to that gained "on the job" but may be significantly more accessible in an undergraduate curricula through virtual educational platforms [2], [7], [8].

While engineering judgment remains elusively undefined, we refer to selected references in the following literature review as a starting point. Without an accepted definition, it is also unclear what kind of experiences provide students with an opportunity to develop engineering judgment. Though limited in its application, mixed reality game-based learning presents an opportunity to shape and understand engineering judgment development. The work presented herein describes an attempt to explicitly define this theoretical construct and apply it to a game-based learning environment with the intent of supporting development of engineering judgment competency in undergraduates while also reflexively improving both the game-based learning environment and the engineering judgment theory.

II. Literature Review

Many geotechnical engineers, practitioners and researchers alike, have made serious efforts to refine the concept of engineering judgment. Ralph Peck, one of the early champions of geotechnical engineering is considered the founder of these efforts, and most subsequent attempts to specify engineering judgment build off of Peck's initial claims. Although Peck himself said he was unable to resolve an all-encompassing definition, he proposed three major skills as a starting point. One skill is a sense of proportion, i.e., the importance of an engineer to have a grasp on the reasonableness of a solution. Peck gives the example that if a practicing engineer has no idea what an average column load for a given building might be, how could they be expected to judge the correctness of a load calculation? A second skill Peck proposed was to establish reasonable criteria, i.e., an engineer should be able to discern which collected data is relevant and how to constrain designs and solutions appropriately. A third skill he proposed was to select and solve the right problem. That is to say, if an engineer does not identify the underlying technical mechanism at hand, they will not adequately address it [9].

Though Peck's reflections on engineering judgment were documented prior to 2000, the evolution of thought on engineering judgment continues into present day. In 2021, Travis Shoemaker of Schnabel Engineering addressed the role of engineering judgment within geotechnical engineering with his term "engineering cognition." Shoemaker particularly focuses on the evolution of communication within geotechnical engineering practice, with modern technology and diverse ways of sharing information, there is no longer any excuse for engineers to not convey their ideas to all stakeholders [10].

Also within recent decades, Lisa Romkey and Yu-Ling Cheng (2009) build on established critical thinking literature to define what they termed the "global engineer". They argue that critical thinking is a good starting place for modern engineers, but upon consideration of engineers' role in society, more guidance is needed in developing a "global engineer". Evaluation of societal, economic, and environmental impacts are all discussed and an idea that a modern society needs a modern engineer is presented [11].

W. Allen Marr, the founder of Geocomp and the 2019 American Society of Civil Engineers (ASCE) H. Bolton Seed lecturer, offered a contemporary perspective in the engineering judgment discussion. Marr leverages Ralph Peck's ideas, but also brings in his experience in industry alongside the well-documented construct of critical thinking. In a 2006 article, he comments on geotechnical engineers' role within the information age, addressing the implications of unavoidable digital disruptions as technology and software become more ubiquitous and powerful. Marr determines that given the inherent uncertainty embedded in geotechnical engineering data, engineers are still vital to the practice due to their ability to exercise engineering judgment. To support this claim, he endeavors to define engineering judgment and ask: "is critical thinking the same as that elusive term we all draw upon and call 'engineering judgment'?" [4]. Referencing "The Delphi Report," a consensus of experts in the critical thinking field, Marr adapts the processes involved in critical thinking to outline a geotechnical engineering process. The six steps outlined in "The Delphi Report" are Interpretation, Analysis, Evaluation, Inference, Explanation and Self-Regulation, which he adapts to the five-step geotechnical engineering process of Investigate, Analyze, Predict, Observe, Evaluate [4], [12]. In 2020, Marr revisits the topic and discards the idea that critical thinking can be viewed as fully equivalent to engineering judgment. He expands upon his initial thoughts and defines engineering judgment as "the exercise of thinking about a problem clearly, logically, and calmly, weighing the known facts, assumptions, missing information, and consequences with considerations of ethical factors, and then deciding on a course of action. It's the ability to come to sensible conclusions about an issue in the presence of incomplete and conflicting information," [13].

Another important contributor to the critical thinking space is Paul and Elder's [14] miniature guide to critical thinking "which provides clear examples of what a critical thinking learner may use in an activity" [2]. They categorize the process of critical thinking into eight "elements of thought" which serve as a launch pad for defining engineering judgment [14]. These elements include concepts that map directly to engineering, such as assumptions and implications.

III. Methods

This study uses qualitative systematic review method, also referenced in literature as qualitative evidence synthesis, qualitative meta-synthesis, or meta-ethnography [15][16]. According to Booth [16], this method "integrat[es] or compar[es] the findings from qualitative studies. The accumulated knowledge resulting from this process may lead to the development of a new theory, an overarching ''narrative,'' a wider generalization, or an ''interpretative translation.'' Whereas a quantitative metasynthesis, or meta-analysis, aims to pool the numerical results of individual quantitative studies, a qualitative meta-synthesis looks for ''themes'' or ''constructs'' that lie in or across individual qualitative studies. The goal of such a qualitative meta-synthesis is not aggregative in the sense of ''adding studies together,'' as with a meta-analysis. On the contrary, it is interpretative in broadening understanding of a particular phenomenon" [16]. To this end, our methods engage purposive sampling with quality assessment used to mediate understanding and generalizations with qualitative, narrative syntheses and grounded theory analytical approaches [15].

Our preliminary search yielded 30 manuscripts from such interdisciplinary fields as geotechnical engineering, higher education, and philosophy. Key phrases in our search were "engineering judgment," "critical thinking," and "engineering cognition." The manuscripts spanned over 25 years and varied in citation magnitude from 5 to over 4,000. This approach yielded sources including prominent academics as well as practicing engineers providing a wide range of perspectives [2].

Each manuscript selected for this study (the references in the Literature Review section are a representative subset) was read for inductive codes, categories, and themes. The constant comparative method was employed for establishing a robust set of codes, which are incidents of recurring ideas that can be grouped into categories by emergent patterns, and further into themes [2]. Emergent themes were further consolidated into a theoretical framework for teaching and learning toward the goal of developing engineering judgment. In the context of this framework, the themes discovered through the constant comparative method represent competencies, including skills and dispositions, that one may improve individually in order to augment their engineering judgment. Consistent with the qualitative evidence synthesis method, one of the representations of our emergent framework is a rubric for assessment of engineering judgment development . This rubric was applied to lab reports resulting from the *GeoExplorer* activity to refine the emergent theory and its practical application. As with literature review, multiple readers reviewed and coded students' reports for each of the emergent themes and any additional recurring ideas. Intercoder reliability between two coders was calculated to be at 85% or above. In this way the emergent ideas were continually updated using constant comparative method and ensuring the robustness of our findings through inter-coder reliability checks.

IV. Results and Discussion

Using a qualitative systematic review, we identify an emergent theoretical framework for engineering judgment that is comprised of seven emergent themes or competencies. Each competency is emergent from a set of emergent categories. Our findings are summarized in the Table 1 below and we provide an example of how open coding and emergent categories from the literature review result in an identification of an emergent theme (or competency) within an overall engineering judgment theoretical framework. As an example, we identified an emerging category of "establish criteria." This category was emergent from an open coding process which included such items as "discern the relevant information," "collected evidence," "understanding the information's applications," "understanding the information's limitations," "determining appropriate assumptions and constraints," and "navigating the problem space" [2]. Some of the instances of the code 'discerning relevant information" and "collected evidence" are found in Marr's 2006 [4] manuscript in such quotes as "Evaluation is sorting the good and useful information from the rest of the clutter" and again with "We have massive data generators pushing information at us all the time. How do we sort the good from the bad?". The Delphi Report [12] also has instances of this code, e.g., "in general, to judge that information relevant to deciding the acceptability, plausibility or relative merits of a given alternative." As well, in DiBiagio & Flaate's biography [9] on Ralph Peck, we used this code when analyzing a quote that reads, "establish reasonable criteria".

This process was repeated across all manuscripts using constant comparative method and all similarly coded instances were mapped to emergent categories shown in Table 1. For the codes in the example above, the corresponding category was identified as "Information and Assumptions." In general, this step then followed by grouping similar categories into emergent themes or competencies. In the example above, the category of "Information and Assumptions" served as an emergent theme of “Establish[ing] Criteria” as we found no other similar emergent category through this iterative process.

In reviewing our emergent theoretical framework for engineering judgment, we find that both critical thinking and engineering judgment rely on one’s ability to constantly update and recalibrate one’s internal database to better understand the root of a problem or issue at hand. Our findings indicate that the key difference between critical thinking and engineering judgment is that exercising the latter must include applying any newfound understanding to ultimately making a judgment [2]. In addition, although critical thinking and engineering judgment are both reflexive processes, exercising the latter necessarily yields a decision. While the process of arriving to this decision is informed by one’s ability to transform to information, it is the critical thinking field that provides instructors with approaches to teaching students how to transform information. For example, critical thinking is taught through emphasis on the importance of a positive disposition toward reflexive thinking.

The interdependent emergent themes or competencies that support the overall emergent theory, can be applied to the *GeoExplorer* project in the landscapes of geotechnical engineering, engineering education, and game design. *GeoExplorer* is a vehicle well suited to developing engineering judgment by providing students with engineering problems that they must solve themselves. The open-ended design allows students to safely engage and develop the same ways of thinking that they will use in engineering practice. It is hypothesized that development of these competencies within a virtual environment will translate to real-life applications for students.

V. Invitation for further Discussion

This paper aims to bring the engineering judgment discussion forth to the engineering education community. As a starting point, we explore limited engineering judgment literature from geotechnical engineering and critical thinking as well as from the broader education scholarship. The critical thinking landscape is vast and well populated by literature. Investigating critical thinking has served the development of an emerging theoretical framework to address the question of how engineering judgment may be developed and assessed in engineering education. Although not in the scope of this particular paper, the application of this emergent framework is synergistically linked to improving *GeoExplorer*, as such, the key question for this work is not just how engineering judgment is developed, but how this process may be mapped to a virtual environment (game). We started applying this framework to *GeoExplorer* and we are still learning. While our findings are preliminary and this work is ongoing, we hope to engage wider engineering education audience in conversation about how our framework may be further developed and applied to a variety of contexts beyond geotechnical engineering and *GeoExplorer* specifically.

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Table I. Summary of Engineering Judgment Emerging Theoretical Framework. Adapted from [17], [2].

Categories	Engineering Judgment Theme (Competency)	Definition
Identification of Problem Space Key Question	Select (and Solve) the Right Problem	The learner engages in identification of the problem space before brainstorming a possible space of solutions. The learner collects a comprehensive data set and relevant resources to identify and characterize the fundamental processes underlying the engineering challenge. They demonstrate understanding of the purpose of the assignment and its engineering significance.
Information and Assumptions	Establish Criteria	The learner understands how to discern the relevant information from the evidence they collect and attends to its applications and limitations. The learner considers the system and makes appropriate assumptions when establishing the criteria (e.g., parameter definitions, appropriate tolerances, system interactions) to constrain the design.
Reflection on Positionality Intellectual Growth and Curiosity	Lifelong Learning	The learner critically reflects on their own positionality as they consider new ideas, opinions, frameworks, and contexts presented by others. The learner demonstrates tolerance for ambiguity and complexity, understands the limits of one’s knowledge, actively seeks intellectual growth, and engages with new methods of thinking (e.g., system thinking) through their work. The learner demonstrates curiosity by actively seeking knowledge from additional resources (e.g., lab manuals, textbooks, publications, etc.) to more broadly understand the purpose of their assignments and the proportion of their expected results (relevant to the particular context of the course, industry method, and/or global context).
Concepts	Concepts	The learner identifies, accurately explains, and appropriately applies the relevant key concepts to the engineering challenge to calculate/synthesize appropriate results.
Interpretation and Inferences Implications and Consequences Definitive Conclusion	Application of Judgment	The learner understands how to apply inferences from these results toward a solution to the task at hand. The learner evaluates the most significant and probable implications and thoroughly considers the potential consequences of the proposed solution from all stakeholders’ points of view. The learner clearly forms a logical and empathetic conclusion and provides justification for the conclusion.
Format and Presentation of Ideas	Effective Communication	The learner presents their ideas with consideration for the following aspects: intended audience, clarity of ideas, precision of language, quantitative analysis, and professionalism. Learners must support their conclusions with data analysis and well-informed quantitative reasoning.
Point of View	Global Engineer	The learner understands that engineering challenges may have multiple effective solutions and can look at the challenge from many points of view in order to assess the benefits for ALL stakeholders. The learner approaches the engineering challenge in the context of optimizing societal wellbeing from all perspectives (ethics, economic feasibility, environmental sustainability, community, region and culture.)

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