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Educational Interventions for Civil Engineering Students: Thematic Review and Future Opportunities*

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Civil engineers play a pivotal role in addressing key societal and global issues. Accordingly, civil engineering educators are tasked with equipping their students with multi-disciplinary skill-sets that empower them to evaluate and solve critical challenges – which include sustainability, safety, transportation, housing, and other infrastructure needs. To accomplish these educational goals, much research has focused on designing, delivering, and testing educational interventions that immerse civil engineering students into relevant learning experiences. The knowledge gained from these research efforts is largely dispersed and fragmented – which is currently a barrier to the development of a robust and proven civil engineering curriculum. The current research summarizes some of the educational interventions that have been developed and tested with students pursuing a civil engineering career to answer questions such as: what problem areas does the developed interventions seek to tackle, what are the characteristics and elements of the interventions, what problem areas have the educational interventions not addressed? The primary objectives of the article were accomplished through a comprehensive review of literature across areas including construction engineering, environmental engineering, structural engineering, transportation engineering, geotechnical engineering, and others. Apart from examining the gaps in the broader literature, the article will serve as a concise resource that can help engineering educators and university administrators develop a robust learning experience for their civil engineering students.

Keywords: STEM education; engineering education; interventions in engineering education

1. Introduction

Civil engineers play a crucial role in the modern society. They are largely responsible for the design, construction, and the operation of various elements in the natural and built environment [1]. These include highways, bridges, dams, homes, water treatment plants, educational facilities, and industrial infrastructure. More recently, civil engineers have also begun taking on a leadership role in managing more global issues that include climate change and disaster relief efforts. Given their significant and varied role in the society, the American Society of Civil Engineers (ASCE) argues that civil engineers are entrusted by the broader society to create a sustainable world and enhance the global quality of life [2]. Accordingly, the American Society of Civil Engineers (ASCE) outlines the role and responsibilities of civil engineers (2007) as being:

- Planners, designers, constructors, and operators of society's economic and social engine – the built environment.
- Stewards of the natural environment and its resources.
- Innovators and integrators of ideas and technology across the public, private, and academic sectors.
- Managers of risk and uncertainty caused by natural events, accidents, and other threats; and
- Leaders in discussions and decisions shaping public environmental and infrastructure policy.

Given the pivotal role of civil engineers in the modern world, civil engineering educators are tasked with equipping their students with multi-disciplinary skill-sets that empower them to evaluate and solve critical challenges – which include sustainability, safety, transportation, housing, and other infrastructure needs. Therefore, these educators must adopt effective instructional approaches that foster learning and skill development among the next-generation of civil engineers.

While there has been research examining instructional methods that have successfully resulted in skill development and learning, this body of literature is highly fragmented and scattered. This is a major barrier to instructors that seek to incorporate effective end influential educational experiences in the curriculum.

The current article examines the body of existing literature to identify effective instructional interventions that have been developed and tested with civil engineering students. The review focuses on diverse areas that include construction engineering, structural engineering, environmental engineering and others. This article will serve as a concise resource that can help engineering educators and university administrators develop a robust learning experience for their civil engineering students. The findings of this effort will equip civil engineering educators with approaches that they can adopt to effectively empower the next-generation of civil engineers to develop industry and society relevant skills. The

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adoption of the interventions reported as part of this article can result in civil engineers that are competent and ready to address key societal and infrastructure needs.

2. Background

Civil engineers address a diverse set of societal challenges. These challenges are often subdivided based on the area of specialization or expertise needed to solve the problems. The most common areas of civil engineering specialization include construction engineering, structural engineering, environmental engineering, transportation engineering and others. The following sections provide a brief background on the problems these areas predominantly seek to address in society to offer context for the educational interventions discussed later in the article.

2.1 Construction Engineering Education

Construction engineering education predominantly focuses on developing skills that are necessary to manage construction projects and build infrastructure elements including bridges, dams, buildings, and others. Accordingly, construction engineering education focuses on a variety of issues that span different industry sectors including residential (e.g., homes), commercial (e.g., shopping complexes), industrial (e.g., power plants), and infrastructure projects (e.g., bridges). Some of the key areas the education seeks to address are:

- Construction Safety (i.e., ensuring worker are safely able to return after work).
- Construction Productivity (i.e., ensuring the efficient use of resources and time in delivering projects).
- Cost Estimation (i.e., Computing the expected cost of planned infrastructure elements).
- Risk Management (i.e., Managing uncertainties and unexpected scenarios that can disrupt project success).
- Cash flow and Finance (i.e., Identifying funding sources and managing cash flow).
- Construction Equipment and Material Management (i.e., Manage and efficiently use project resources).
- Scheduling (i.e., Establishing the means and methods and identifying the optimal sequence of construction tasks).
- Quality (i.e., Ensuring that the constructed infrastructure elements meet required standards and specification and the reduction of unnecessary rework).

2.2 Structural Engineering Education

Unlike the construction engineering focus, the structural engineering education predominantly focuses on the design of structural elements that are safe when subjected to a variety of loads and forces which include the self-weight of structural elements, the occupancy or live load, wind load, earthquake load, snow load and others. The education that these engineers receive includes the design of structural components that are subjected to bending, compression, tension, and a combination of these loads and forces. In practice, these engineers are often with designing beams and columns for residential and commercial construction projects, girders and decking for bridges, and boilers, storage tanks and furnaces for industrial projects, among others. Some of the key areas that education in the area of structural engineering include:

- Engineering Mechanics, Statics, and Dynamics (i.e., Response of objects or bodies under the action of forces).
- Structural Analysis (i.e., Behavior of structures when subjected to forces and stresses).
- Concrete design (i.e., Design of structural members using concrete as the primary construction material).
- Steel design (i.e., Design of structural members using steel as the primary construction material).
- Wood design (i.e., Design of structural members using wood as the primary construction material).
- Building System Design / Bridge System Design (Design of building and bridge structure elements).

2.3 Environmental and Water Resources

Engineers with the focus on environmental and water resources focus on a plethora of areas including sustainability, energy consumption, water conservation, waste management and other factors that can influence the environment and water resources. These areas have particularly become important given the detrimental effects the activity of humans have had on the environment and its resources. While there is a large body of topics that are covered as part of the educational experience of students in these areas, a few of the common focus area are presented below:

- Sustainability (i.e., maintain and improve the quality of life while preserving the natural environment).
- Waste Management (i.e., recycling, treating and disposal of residential, industrial, biological, and other wastes).
- Life Cycle Assessment (i.e., assessment of the

impact of a product or practice throughout the operation period).

- Environmental preservation (i.e., Identify and adopt interventions that can reduce air pollution, water pollution, and the preservation of all natural resources).
- Water and Sewage treatment (i.e., effective processes to treat and manage water and sewage from various sources).

2.4 Transportation Engineering

These engineers deal with a variety of transportation issues and devote their efforts in ensuring the smooth transportation of goods and commodities. They play a critical role in fostering economic development by ensuring the availability and the operations of bridges, highways, airports, seaports, and other modes of transportation. The education of these engineering generally focuses on diverse topics that are relevant to the design, operation, and maintenance of transportation infrastructure and relevant public assets. While there are a variety of operations and functions these engineers undertake, a few example activities include:

- Highway and Bridge layout (i.e., Identify optimal routes for effective transportation).
- Traffic Engineering (i.e., Managing the efficient flow of traffic by using planning techniques, signage, highway marking, etc.).
- Highway Safety (i.e., Assess causes of traffic incidents and identify appropriate safety solutions).
- Airport and Railway Engineering (i.e., Plan and coordinate the construction, maintenance, and the operations of various transit systems).
- Forecasting travel and Traffic Flow Planning (i.e., Identify travel needs of commuters and provide solutions to foster the uninterrupted flow of traffic).
- Asset Management (i.e., Maintain public infrastructure elements such as highways and signage effectively).
- Transportation Material Science (i.e., Identify and adopt effective materials for infrastructure project construction and maintenance).

2.5 Geotechnical Engineering

Geotechnical engineers predominantly focus on soil mechanics, properties of soils, seepage in soil, ground improvement techniques, subsurface exploration, foundation engineering, and the effective retention of soil and rocks. As part of their professional careers, these engineers focus on various areas, but some of the common areas are as follows:

- Foundation Design (i.e., Propose suitable foundations types based on soil types).
- Subsurface exploration (i.e., Adopt engineering techniques to understand properties of soils in areas of interest).
- Soil Stabilization (i.e., Stabilize soil by using various techniques such as slopes, geosynthetics, retention walls, and other approaches).
- Ground Improvement (i.e., Use engineering techniques to improve soil bearing capacity and soil properties).

As discussed above, civil engineers play a pivotal role in addressing a plethora of engineering and societal challenges. To ensure they are able to effectively and efficiently address the great number of engineering challenges, robust and reliable educational approaches must be adopted by instructors. Identifying these techniques that foster skill development and learning among this cohort of engineers will enhance their educational experience and their ability to contribute to the needs of the society. Accordingly, this article seeks to bring together the fragmented body of literature that examines educational interventions that have been successfully used as part of civil engineering education.

3. Research Methods

Given that the objective of the article was to examine and summarize educational interventions that have been developed and tested with civil engineering students, various search engines were adopted to examine the literature. The search engines that were used included Web of Science, Engineering Village, and the databases maintained by the American Society of Civil Engineers (ASCE). Various search terms including education, intervention, and training along with the titles of the various areas of civil engineering discussed above were used as search terms.

The search generated thousands of articles. However, a closer look at the articles revealed that only a relatively few studies empirically tested interventions, although various studies focused on proposing various educational approaches. Nonetheless, the objective of the current study was maintained to examine the various interventional studies that were performed in the context of civil engineering research. Most of the articles were published within the last two decades. The following sections summarize the interventions that were relevant to each of the civil engineering areas.

4. Research Findings

The following sections discuss the educational approach and the thematic focus of the literature organized based on the area of focus as presented in the background section.

4.1 Construction Engineering Educational Interventions

Among the educational intervention studies in the construction area, a large number of studies adopted virtual environments for educational purposes. For example, Pena and Ragan [3] used a virtual environment to simulate construction accident reports to foster learning that is useful for injury prevention. Several other studies have particularly examined virtual environments and augmented reality for construction safety applications [4]. For example, interventions have been developed to improve hazard recognition ability among students and other construction personnel [5, 6], communicate essential safety information [7], model efficient and safe work operations [8], foster collaborative and social learning [9], and demonstrate the safe use of construction systems and structural elements [10]. Much of these efforts have adopted virtual environments and augmented reality because of its enhanced ability for creating realistic and representative visualizations of what individuals would experience in the construction industry.

Apart from safety applications, serious games have been used for presenting students with details on the construction bidding process [11–13], the effect of weather and labor productivity on project management challenges [14], collaboration between various trades undertaking diverse activities [15], equipment management [16], defect identification, and supply chain operations [17]. These studies have leveraged the engagement that students and construction personnel experience when being involved in a game that also presents educational benefits.

Efforts have also used 3D models, Building Information Models (BIM), and simulation techniques to demonstrate the construction assembly process to improve efficiency and achieve cost savings [18, 19]. Augmented reality has also been used for the same applications such as the assembly of pipelines. [21] and bridge components [22]. A few studies have also adopted telepresent techniques where live videos with augmented reality solutions are used to present real construction operations to students. These efforts demonstrate that students enjoy the interactive and engaging educational experiences that technology offers.

Other educational interventions have successfully leveraged the benefits of flipped classroom sessions followed by interactive social learning experiences [23]. These efforts exposed students to a variety of topics which include ventilation, air-conditioning, plumbing work and others. Efforts have also used mnemonics, problem-based learning, and immersive experiences for a number of construction educational efforts [6, 24–26].

Overall, much of the recent research in the area of construction engineering adopted emerging technologies to foster visualization and immersive learning experiences to promote the achievement of educational objectives. Other techniques include problem based learning, flipped classrooms, and the use of mnemonics.

4.2 Structural Engineering Educational Interventions

A large number of structural engineering educational interventions have focused on experimental and experiential learning methods. For example, educators have adopted physical models of structures that are subjected to varying types of loads to demonstrate structural behavior. For example, the behavior of structures in response to seismic loads [22] and the behavior of structural elements (e.g., column) in response to particular load types (e.g., bending, compression, etc.) have been incorporated as part of educational interventions [27, 28]. Such demonstrations and experimental set-ups have offered students to witness the behavior of structures or structural elements (e.g., deflection) which is important to developing effective mental models or representations of structural engineering concepts.

Apart from real physical testing, testing has been demonstrated in virtual environments, augmented reality, and using computer simulations. For example, these techniques have been used to demonstrate the various parts of a structure, the response of structural elements to particular loading scenario, response of structures to seismic loads, and others [29–32]. The use of virtual and augmented reality educational interventions offer the ability to easily communicate the behavior of structures and structural elements while also ensuring safety. This allows the simulation of various scenarios that may not be safe to model and test physically for educational purposes. Moreover, it allows the demonstration of structural behavior where it would not be financially feasible to construct a physical structure or structural element to model particular responses. In several other cases, educators have used virtual serious games to better engage students in the educational process [33] such as in the design of trusses and other structural elements.

In several cases, structural engineering education has combined the use of both virtual experiments or simulations along with physical testing. For example, there are examples of studies where educators simulate the behavior of structures in a virtual environment which is then replicated using physical models [34, 35]. In other words, in these cases educators often demonstrate that their prediction based on the response captured in the virtual environment generalizes to the behavior of structures in the real or physical world.

Another educational approach that has been used as part of interventions is the use of problem based learning approaches [24, 36, 37]. These interventions present students with a practical problem and encourage them to propose and compare prospective and potential solutions. In another recent study, 3D printed models of structural elements were used for disseminating design principals [38].

4.3 Environmental and Water Resources Educational Interventions

A number of educational approaches have been adopted for environmental research. Many of these were experimental in nature where the students themselves led the experiments or were led by instructors [39–41]. These experiments focused on a variety of topics including the preservation and the remediation of environmental attributes that include air, water, and soil. For example, students have examined water quality where samples were gathered from various venues including a water treatment plant and local schools to measure and compare the presence of impurities. Others have demonstrated the effect of mold spore in indoor air quality. Sustainable concepts have also been demonstrated using experimental approaches [41].

Virtual labs have also been used to foster learning and engagement among students. For example, virtual set-ups have been used to disseminate knowledge related to forest management [42], effect of chemical plans on the environment [43], and others environment-related issues. In some cases, interventions have also combined physical testing and the use of simulations to foster and reiterate environmental and water resources related educational material [44–46].

Case studies have also been commonly used to demonstrate the complexities of environmental challenges and the effects of sustainable interventions [47]. In some cases, instructional methods have also used role-playing and interviews with industry experts to communicate environmental challenges and sustainable solutions [48]. These case studies in several cases offered students with a project-based learning experience where a project with particular environmental challenges was presented to students who are then tasked with identifying feasible and effective strategies to address key environmental and societal challenges. Examples of such learning experiences have been particularly adopted in the context of sustainability related issues [49–51].

Active and hands-on learning experiences have also commonly been used as part of educational interventions for environmental engineering students [52, 53]. This has been accomplished in many ways. For example, service level and community service activities have been effectively leveraged for educational purposes [54, 55].

4.4 Transportation Engineering Educational Interventions

Much of the instructional approaches in the transportation engineering literature adopted computer-based simulation approach for instruction. For example, simulations have been used to examine traffic volume and factors that influence the need and construction of new highways [56]. Simulations have also been used to instruct students regarding the timing plans for signals [57]. Other applications of the use of simulation in the transportation engineering context include exposure to transportation engineering planning processes [58], designing highway layouts on the basis of contour maps [59], and the process of operating airlines [60], and the operation and the optimization of traffic signal functioning and placement [61].

Educational interventions have also used visualization and virtual reality techniques. These applications were used to demonstrate the operation of traffic signals in relation to vehicle progression [62], development of highway networks in a city context [63], and the interaction between vehicles, pedestrians and other contextual factors in a transportation setting [64].

Other interventions that were used included problem based educational approaches where interventions focused on the effect of policy and traffic volume [65], pavement design [66], and earthwork operations. Interventions also used case studies of particular highways to communicate issues with traffic in city limits [67]. Several other interventions also adopted educational experiences that involved hands-on activities and traditional instructional methods.

4.5 Geotechnical Engineering Educational Interventions

A number of educational interventions have been used in the geotechnical engineering context. Several of these interventions have used physical models. These models have been used to demonstrate several geotechnical concepts such as pore water pressure, soil liquefaction, soil pressures, and the effect of soil consolidation [68, 69]. Laboratory experiments with soils are also used as part of geotechnical education. For example, an effort has focused on demonstrating permeability and the flow of contaminants through soil [70]. Apart from these physical models, virtual demonstrations of the behavior of soils have also been modeled to enhance student learning and understanding [71].

Various multimedia presentations depicting engineering failures in the context of geotechnical engineering has been used as demonstrations. For example, geochemical challenges have been demonstrated in the context of the Leaning Tower of Pisa, dam failures, and building failures [68, 72]. Documentaries that depict landslides and forensic analysis have also been used as educational tools [73]. Tools such as online educational shake tables have also been developed and tested to improve education in the area of geotechnical education [30].

Apart from the educational approaches discussed above, other approach such as project based and problem based educational intervention are also reported in the literature [74]. The use of case studies to discuss the interaction between soil and the structure that the soil supports has also been used for illustrative purposes [75].

5. Lessons Learned, Discussions, Recommendations, and Future Opportunities

The above sections summarize some of the interventions that have been leveraged to foster student learning in the focus areas within civil engineering. As can be seen, a large number of interventions in the construction engineering focus area adopted virtual environments and augmented reality for different applications. Most of the interventions also targeted the construction safety area. Relatively lesser work has focused on education as it is relevant to scheduling a project, managing cash flow, and the operation of equipment – although they are fundamental areas in the construction engineering area as discussed in the background section. Problem-based and project-based learning experiences were also limited in the broader literature. Future research can potentially target these areas.

Structural engineering education has predominantly used both physical and virtual environments for demonstrations and learning. Most of the interventions observed in the literature focused more on introductory courses in the area of structural engineering – such as structural analysis and strength of mechanics. A few interventions that were particularly relevant to earthquake engineering and structural dynamics were also represented in the literature. Only a few problem-based educational interventions were found in the literature. Use of problem-based and project-based interventions may be an area where structural engineering education can focus to a greater extend.

Most educational interventions in the environmental engineering area adopted experiments as a learning tool. These efforts provided students with a first-hand experience of common environmental problems. In a few cases, virtual environments and labs were also adopted for demonstration purposes. However, a lesser proportion of the use of virtual environments compared to the other areas seemed to be the trend. However, a considerable amount of studies used case studies and problem-based educational interventions for a variety of applications. The literature appeared to more effectively cover most of the key areas in environmental engineering including environmental preservation and sustainability concepts.

The most common educational approach found

Table 1. Summary of educational intervention elements and propounded benefits

Educational Intervention Elements	Example Benefits
Virtual Environments / Serious Games / Virtual Labs / Digital Simulations	• Risk-free and safe environment from physical hazards • Simulation of rare and unsafe situations • Practice desirable behaviors • Demonstration and visualization of key concepts and assemblies • Engagement using game elements
Physical Models and Simulations	• Visual examination of key processes and mechanisms
Problem and Project Based Learning	• Exposure to practical problems and projects • Intellectual challenge of proposing feasible solution
Experimental Education	• Hand on experimentation offers the students to directly experience cause and effect relationships
Case Studies	• Exposure to problems and challenges that were experienced in the past • Insights into how the problems and challenges were resolved
Service and Community Activities	• Addressing key societal problems using hands-on efforts
Industry Expert Interactions	• Exposure to key societal problems and the state of the practice • Development of relationships that foster career development
Multimedia Educational Elements	• Videos, images, and documentaries demonstrate key engineering challenges • Visualization of solutions that were adopted to address key challenges
Physical Models	• Physical demonstration of real-world behavior and issues on a small scale

in the transportation area appeared to be the use of simulations. In a number of cases, virtual environments were also adopted to particularly demonstrate the operation of traffic signals and the relation with commuters and pedestrians. Problem-based and project based interventions were also common. Most of the interventions appeared to focus on highway-related educational experiences. More work could be focused on other transportation modes.

Geotechnical engineering mainly used physical models and experiments as part of the instruction. The use of multimedia and documentaries have also been documented in the literature. Project based learning was also relatively common. More interventions can be adopted in the future to demonstrate the use of geosynthetics and ground improvement techniques which were less common in the broader literature.

The results also revealed that there were similarities in the interventions that were adopted across the civil engineering areas examined in the current study. Table 1 offers a summary of the educational intervention elements found across the studies and the associate propounded benefits. Educators can use the summary table to select particular intervention elements of types in accordance with the desired learning outcomes.

6. Conclusion

Civil engineers must be prepared to effectively meet key societal and industry challenges. Accordingly, civil engineering educators are tasked with fostering learning among civil engineering students. These instructors play a major role in equipping students with necessary skill-sets to effectively contribute as part of their professional life. Accordingly, robust and effective educational interventions must be adopted as part of civil engineering education.

To foster such learning, a number of educational interventions have been developed which target the civil engineering study body. However, the body of literature that discusses these educational interventions is largely dispersed and fragmented. This is a significant barrier to the adoption of effective educational interventions – particularly when educators are unaware of effective educational interventions that have been developed and tested.

To serve as a resource to civil engineers, the reported research examined educational interventions that were developed for the various focus areas in civil engineering. This included construction engineering, structural engineering, environmental and water resource engineering, transportation engineering and geotechnical engineering.

In each of these areas, the research examined the intervention types that have been adopted and the area of focus that the intervention targeted. Educational intervention types included the use of virtual environments, augmented reality, multimedia, physical models, physical demonstrations, experimental demonstrations, problem based learning, project based learning and the use of case studies. Civil engineering educators can adopt, adapt or replicate the discussed educational approaches discussed in the article. The adoption of the discussed educational interventions can help develop robust learning experiences and equip students to better address societal challenges.

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