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Immersive learning through virtual reality for civil engineering education

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ABSTRACT

This academic work focuses on creating and assessing a Virtual Reality (VR) learning tool designed for civil engineering education. The tool aims to help students understand complex construction phenomena better by providing laboratory and real-world simulation-based construction scenarios. With the aid of immersive learning offered by VR, the gap between theoretical and practical knowledge is narrowed, and issues such as limited site access, safety requirements, and logistical challenges are mitigated. The study employs a systematic approach to development, including needs identification, tool creation, and evaluation after the tool is developed. The use of paired t-tests enables quantitative analysis of the data. It reveals improved learning outcomes among students utilizing the developed VR tool compared to traditional methods. In addition, students with VR perception reported high ease of use and satisfaction scores. The results emphasize how VR technology can cultivate critical 21st-century skills like problem-solving, collaboration, creativity, and constructive technological engagement. VR can deliver students with safe, inexpensive, and easy-to-scale solutions that offer a wider range of construction learning that was impossible to provide in the past. This study aids a growing understanding of innovations in teaching and learning technology in civil engineering education, especially the importance of VR in preparing them for Industry 4.0. More research should investigate the sustainability of the impacts of the VR environment on learning among engineers from different specialities.

Keywords: virtual reality, immersive learning, civil engineering education, technology-enhanced learning

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INTRODUCTION

The reality of the construction world is that students need to use their hands and get practical in building to gain a holistic understanding of how things work (Muslihati, 2023; Sun et al., 2022). In construction, it is customary to teach using site visits and lab trips (Eiris et al., 2021). Unfortunately, due to expensive budgets, complicated planning of site visits, limited project scope, and the widespread COVID-19 pandemic, students have had far less access to these practical environments (Chenari et al., 2024; Köpsel et al., 2021; Lewis et al., 2024; Montiel et al., 2021). As a result, students primarily learn theory in the classroom, which puts them at a disadvantage when learning about constructions in the field.

New technologies like virtual reality (VR) are increasingly being adopted in teaching, looking at these obstacles. VR provides a life-like environment where students can use their eyes and hands to get involved in complex construction processes right from their classroom (Beck, 2019; Bower et al., 2014; Makransky & Lilleholt, 2018). With VR, students can experience their first virtual site tour and steps to the construction without risk, making it cheap and easy (Radianti et al., 2020; Xiong et al., 2021). Many pieces of research provide evidence that VR aids in maximum focus, understanding, and academic performance in almost all subjects, from science to engineering (Concannon et al., 2019; Innocenti et al., 2019; Radianti et al., 2020). Despite its proven potential, VR in construction education remains underutilized, with most efforts focusing on theoretical applications rather than replicating real-world construction environments.

While VR has been widely explored for science and bridge construction courses, a noticeable gap exists in its application for comprehensive building construction education. Existing VR applications often lack the interactive and immersive elements to replicate practical construction site experiences fully (Allcoat & von Mühlenen, 2018; Chou, 2017; France et al., 2016; González et al., 2013; Slavova & Mu, 2018; Xavier et al., 2019; Zhou et al., 2018). Furthermore, limited research evaluates user perceptions and the effectiveness of VR as a learning tool in civil engineering education, particularly in Indonesia and similar contexts.

The objective of creating a specialized VR learning tool for building construction education regarding the gaps identified is to create a specialized VR learning tool for building construction education. This tool replicates actual construction sites to facilitate students' interaction in different construction activities. The study investigates the user impressions of the developed VR tool and establishes baseline insights into its effectiveness.

This research is novel because it seeks to integrate theoretical and practical aspects of construction education through VR technology, especially in areas that lack physical site access. It provides one of the many solutions to the perennial problems of construction education, fostering students' more effective learning and readiness for real-life construction projects.

This research provides several key contributions: 1) Design and fabricate a VR tool for Education on building construction that mimics real-life situations. 2) Completing the assessment of the initial performance metrics of the tool regarding civil engineering education. 3) Checking the users' perceptions will provide construction education with further developed and optimized VR learning tools.

METHOD

This study systematically designs and evaluates a virtual reality tool to support civil engineering education. The methodology consists of three main stages: pre-development, development, and post-development, as shown in Figure 1. A needs assessment defines educational and technical needs during the pre-development stage. The literature evaluation established what materials for VR-based learning can be used, ensuring the components fit within the civil engineering subject syllabus and the specified learning outcomes. This phase also looked at hardware VR sets and smartphones, software(s) Unity or Unreal Engine, content components, 3D models, and interactive scenarios as technical components. This assessment prepared a comprehensive content development plan, including media and content validation criteria.

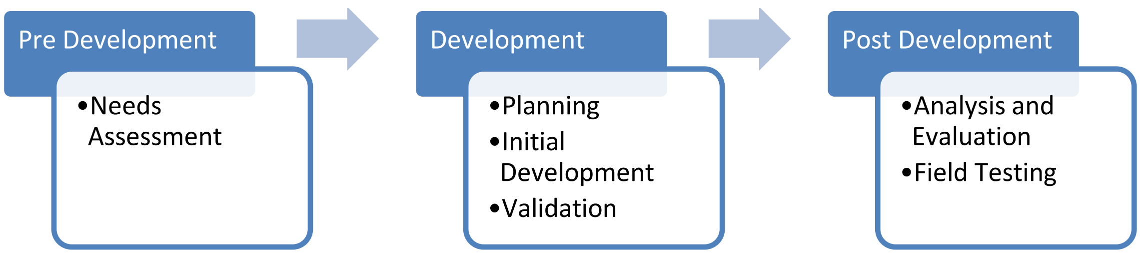

Figure 1. Development procedures

This stage was concentrated on developing and polishing the VR tool. Three-dimensional models and simulations of construction sites were developed for an engaging and interactive teaching and learning experience. The tool was implemented in VR Unity and included the main parts of the system: navigation, interaction with the environment, and multimedia presentation of information, including visuals and sound. Validation was done in two domains: media and content. Media validation was done by the experts who evaluated the technology, its usability, and the interface design. In contrast, content validation was done by the civil engineering tutors to check if the material was relevant and accurate for instruction. Suggestions from these evaluations facilitated changes to the VR tool.

The final phase of development sought to measure the effectiveness of the VR tool. The tool was piloted on 30 civil engineering students in two classes, each comprising 15 students. One of the classes acted as a control and received instruction in civil engineering through conventional classroom teaching. In contrast, the experimental class received instruction through the VR-based learning tool. Quantitative information was obtained through pre- and post-test scores from both groups.

In contrast, qualitative information was obtained by analyzing narrative feedback and perceived usefulness questionnaires. The effectiveness of the VR tool was evaluated, and initial effectiveness was determined descriptively. The adjustments to the student's feedback were analyzed thematically and meshed together.

This study contributes to an emerging literature that seeks to demonstrate the effectiveness of the VR tool in attempting to improve the learning of civil engineering students. The outcomes from the statistical analysis and the resulting feedback are helpful for further developments and attempts to integrate VR Technology into construction education.

FINDINGS AND DISCUSSION

The results and findings of this study will be presented here in an organized form to ensure that the research outcomes can be easily understood. Findings are presented first, followed by a detailed discussion that interprets what the findings imply. This section intends to clearly explain the experiments' results, their meaning, and the possible conclusions that may be drawn. Because this purpose is essential, it is also one of the most important parts of the article. The discussion covers product specification innovations, civil engineering VR applications, assessment criteria, and the prospects of VR in Education and industry. This study investigates the role of VR technology in teaching, its integration with classical physics, and engineering practices needed to solve practical problems.

Findings

Innovative VR integration for building construction education

The goal of using video virtual reality (VR) is to assist students in understanding concepts in a building construction course, especially in practical areas like stonework and rebar placement. The VR system fuses two teaching styles: the laboratory approach and real-life fieldwork. Students can participate in virtual simulations where they first see the construction process in a controlled laboratory environment and later check how it is done at different construction sites. For example, in the stone and rebar practice module, learners are taught how to build and fit the reinforcement bars (rebars) into columns and beams. The application of virtual reality enables the student to learn all the tools and materials needed, how they are fabricated, and the occupational safety and health (OSH) standards governing laboratory training.

Outside of the laboratory context, the VR application boosts learning by representing the entire sequence of rebar production and its application on actual construction sites, such as buildings and bridges. This combination of virtual reality with practical knowledge creates an opportunity to learn meaningfully, unlike typical VR applications, which focus on explaining concepts in a virtual world. By learning through practice, students will benefit significantly regarding civil engineering. The VR system allows the students to acquire construction-related skills, increase understanding, and be better prepared for real-world work situations in a safe and realistic environment.

Advancements and applications of virtual reality in building construction engineering

The construction industry has been transformed by VR technology, which has further developed the practical aspects of civil engineering and augmented the theoretical knowledge of the field. Concepts in Civil Engineering often tend to be very complex as they deal with abstract ideas that are purely theoretical and need to be complemented with practical learning. Students can experience this abstract theory with a higher level of ease through simulations. VR makes this learning process more effective by repositioning static text and visuals into dynamic 3D environments that students can interact with. Through virtual reality, students can interact with different phases of construction projects, from building the foundation to constructing the roof. For example, in soil mechanics courses, students are immersed in virtual environments where they can adjust their size to experience and visualize the behavior of soil particles. Shrinking to microscopic dimensions means students can navigate through muddy pores. At the same time, water flows through them as the soil is compressed. This immersion type guarantees a better understanding and retention of challenging engineering concepts.

VR technology allows the elaboration of sophisticated design and construction processes, enabling students to interactively engage with concepts of structural engineering and their analysis. For example, in bridge foundation design, students can operate in a virtual world where they can assess load capacity and define the dimensions of the foundations. This digital approach helps students fine-tune the designs, get automated responses from computer-aided evaluations, and make necessary changes. A key problem for civil engineering students is the scarcity of laboratories and expensive research equipment. VR lessens this problem by providing an economically friendly, secure, and easily adjustable solution for hands-on learning. Incorporating virtual simulations in addition to real-life experiments enables universities to improve the quality and effectiveness of training programs in civil engineering.

Practical training exercises are an important part of the learning process in civil engineering studies, particularly regarding construction processes. Conventional fieldwork, however, has problems such as safety issues, time limitations, and boundary restrictions. The number of students taking part in site visits usually outnumbers the instructors available, which means there is little guidance provided, and ultimately, there is little they learn. Moreover, some construction sites are off-limits for students for safety reasons. VR solves these problems because students can virtually participate in complete construction exercises, step-by-step procedures, and construction details without risk. In addition, to enhance students' understanding, important points of construction work are illustrated in detail within the sophisticated 3D models. The illustrative VR models for building construction are presented in Figure 2.

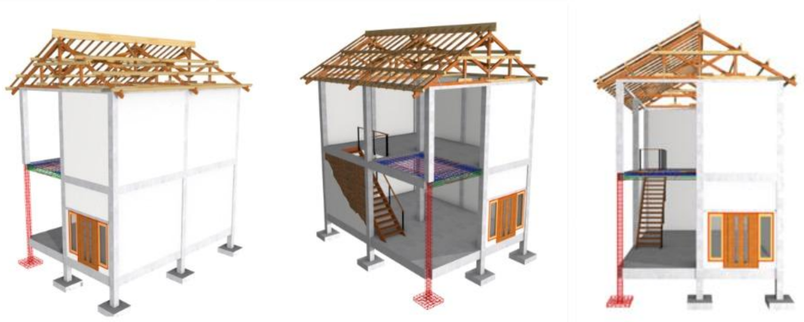

Figure 2. (a). Exterior perspective view of a building model with an open roof for construction illustration

Figure 2 (b). Frame structure and foundation building model showing details of reinforcement and other structural elements

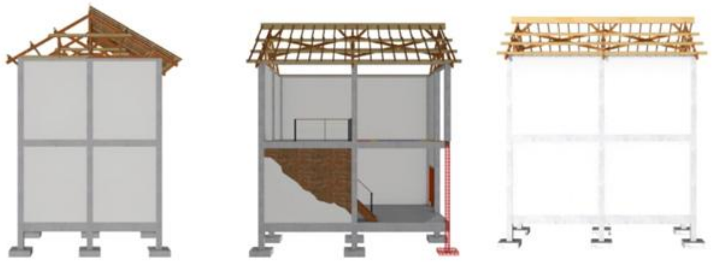

Figure 2 (c). Vertical and horizontal sections of the building showing the distribution of structural elements and interior layout

The construction progress can be viewed in Figure 2 (a). This design opens an exterior view of the building model with the removable roof. The students can then observe various building parts erected without physical barriers. Figure 2 (b) depicts a cross-section of the building model that contains a grid detailing the positions of the reinforcements and slabs. Students studying this model can appreciate the concepts of structural control and the steps taken to achieve them. As for the last part of the sample material, vertical and horizontal cross-sections of the building are presented in Figure 2 (c). Students can see how the components of the structure and provide services within the building are assembled. The students are visually submerged in a plausible real-life construction project scenario to appreciate construction engineering principles.

A detailed comparison between VR-based practice and conventional on-site learning is provided in Table 1. The table highlights the key differences, including risk factors, costs, and overall convenience. Unlike on-site training, where students are exposed to potential hazards associated with heavy machinery and construction environments, VR eliminates safety risks by providing a controlled digital environment. Additionally, traditional fieldwork is often constrained by time and space, limiting students' ability to observe complete construction processes. Conversely, VR offers an unrestricted learning experience with the ability to revisit simulations anytime. These advantages make VR a powerful tool in supplementing and enhancing traditional field training.

Table 1. Comparison of the VR application and on-site practice

Main Feature	VR-based Practice	On-site Practice
Realization	VR laboratory	Real action (Heavy vehicle, field)
Risk	None	Mid-high (depends on the project)
Cost	Low	High
Space and time	Unlimited	Limited to the space and time
Convenience	High	Low

Effectiveness of VR-based learning: Statistical findings

A paired t-test was conducted, comparing a control group (traditional teaching) with an experimental group (VR-based learning) to evaluate the impact of VR on students' learning outcomes. As shown in Table 2, the test results indicate a significant improvement in learning outcomes for students who utilized VR. The t-value of 4.416 is greater than the critical value (df = 14, 1.761), confirming a statistically significant difference. Furthermore, the two-tailed significance value (0.001) is well below the 0.05 threshold, reinforcing the positive impact of VR on student performance. The mean score of 17.3 suggests that students in the VR-based learning environment demonstrated marked improvements compared to their peers in traditional classrooms.

Beyond statistical improvements, student feedback was collected to assess their perceptions of VR technology in civil engineering education. Table 3 summarizes students' perceived ease of use and effectiveness of VR-based learning

Table 2. Paired T-test result

	Mean	t	df	Sig. (2-tailed)
Two Groups	17.3	4.416	14	.001

Table 3. Students perceived ease of use on VR-based application

No	VR Component	Students' Perceived Ease of Use
1	The VR-based application can convey material in the field of building construction	91.67%
2	The contents of VR can explain the learning content correctly	90.63%
3	Proper animation in VR	86.46%
4	Proper text in VR	89.58%
5	The design of VR can make it easier for students to learn	87.50%
6	The visual design of VR can make it easier for students to study	87.50%
7	Audio appeal designed to facilitate teaching understanding	84.38%
8	Text design and text in teaching materials make it easier for students	86.46%
9	Design combination, arrangement, and color selection in VR are convenient	85.42%
	Average	87.72%
	Standard Deviation	2.43
	Minimum	84.38%
	Maximum	91.67%
	Median	87.50%
	Variance	5.91%

From Table 3, the overall average score of 87.72% indicates a highly positive response, suggesting that VR effectively enhances learning experiences. The highest-rated aspect, with 91.67%, is the VR application's ability to convey construction materials, demonstrating that students find VR more effective than traditional methods. Additionally, 90.63% of students agree that VR accurately explains learning content. The clarity of text (89.58%) and the effectiveness of visual design (87.50%) further support the idea that VR enhances comprehension through an intuitive and structured presentation.

The animation quality (86.46%) and the combination of design elements, layout, and colour selection (85.42%) also received favourable ratings, indicating that the aesthetics contribute positively to the learning experience. However, the audio component received a slightly lower score (84.38%), suggesting potential room for improvement in auditory engagement. Overall, the findings confirm that VR offers a practical, engaging, and interactive learning approach in civil engineering education, bridging the gap between theoretical knowledge and practical application while addressing the limitations of traditional fieldwork

Discussion

Prospects of virtual reality in civil engineering

Civil engineering is witnessing a new paradigm in which entire virtual worlds can be constructed and traversed. Virtual reality has made huge strides compared to flythroughs, simple walkthroughs, or rendered animations. In modern VR systems, users can directly select, manipulate, or control objects within a designed environment. This advancement places VR beyond an advanced 3D visualization tool to a powerful instrument through which design decisions can be made. Using VR, engineers can build structures in an immersive setting instead of relying on 2D Computer-Aided Design (CAD) packages, making the design process much more straightforward (Safikhani et al., 2022). However, further progress must be made for VR to be integrated into Civil engineering, especially in crafting intuitive and effective interfaces that will facilitate efficient use.

Virtual Reality Modeling Language (VRML) enables the construction of 3D interactive settings, one of the core technologies that facilitate using VR applications. Due to its ability to support transformations, animations, multimedia, and real-time interactions, VRML is a powerful resource for engineering design and simulation. Coupled with suitable programming languages and the internet, VRML can be used to devise modern applications that improve engineering and project management training (Zhu & Xie, 2024). This allows civil engineers to go beyond visualizing their designs and enables them to interact dynamically with the design, modify elements, and evaluate practical impacts before actual construction work.

Besides design uses, VR is becoming increasingly prevalent in construction safety training. One example is the Safety Analytics Virtual Reality (SAVR) system, which enables users to recognize and deal with hazards at the workplace, such as missing guardrails, loose components, or scarily unstable scaffolding (Dhalmahapatra et al., 2022). With the aid of VR headsets, workers can get transported to virtual construction sites and learn effective safety measures without putting themselves in danger. The SAVR system uses a scoring method to determine users' performance, remind them, and reinforce learning outcomes. Similarly, other Occupational Safety and Health Administration (OSHA)--based VR safety training programs can give warnings and other safety instructions as users approach dangerous zones in the virtual world. Such developments render VR a promising tool for improving safety and compliance in the construction sector.

It should also be noted that VR is being incorporated into the management of construction projects to improve communication and visualization. Project management systems have traditionally operated on the 2D model, which is hard to interpret and easily miscommunicated. VR-based systems are far more user-friendly as they allow all relevant stakeholders to view the construction progress in 3D, making it easier for them to plan and coordinate. For instance, engaging in a schedule-based VR simulation enables real-time monitoring of project progress, which means that engineers and project managers can actively manipulate construction timelines (Zhang et al., 2022). In this way, VR is bound to become far more important in the future of civil engineering as it helps bridge the gaps between design, safety, and project execution.

Relevance to 21st-century education

The findings of this study underline the importance of VR technology in skills-based learning in civil engineering education. In the scope of the 21st century, education, communication, collaboration, critical thinking, and creativity are crucial for solving contemporary engineering problems. VR helps achieve these skills by offering safe, interactive, and engaging real-world scenarios (France et al., 2016).

Immersive VR environments allow students to engage in complex, real-world scenarios without the associated risks. For example, VR simulations allow learners to explore various construction sites, analyze potential hazards, and make informed decisions in a controlled setting (Xavier, 2019). This experiential learning approach has improved students' critical thinking and problem-solving skills, as they must navigate and respond to dynamic situations that mirror actual engineering projects (Beck, 2019; Innocenti, 2019). A study highlighted that VR-based learning media in building construction courses effectively enhanced students' understanding of complex concepts, thereby improving their problem-solving abilities.

VR technology facilitates collaborative learning by enabling multiple users to interact within the same virtual space. This shared environment allows students to work together on engineering projects, such as designing and constructing structural models, mirroring modern industry practices emphasising teamwork and communication (Chenari et al., 2024; Concannon, 2019). The collaborative nature of VR-based learning enhances students' technical skills and prepares them for the interpersonal dynamics of professional engineering roles. Research indicates that integrating VR with challenge-based learning approaches fosters student engagement and collaboration, leading to a deeper understanding of construction systems in civil engineering education.

One of the significant advantages of VR in civil engineering education is its ability to bridge the gap between theoretical instruction and practical application (Radianti, 2020). Traditional classroom settings often struggle to convey the complexities of real-world construction environments. VR addresses this challenge by providing immersive simulations where students can apply theoretical concepts in practice, such as virtually constructing building components or managing project workflows (Xiong, 2021; Zhu & Xie, 2024). This hands-on experience is crucial for reinforcing learning and ensuring that students are well-prepared for the demands of the engineering profession. Studies have demonstrated that VR applications in civil engineering education enhance students' comprehension of construction processes and improve their readiness for real-world challenges.

CONCLUSION

Virtual reality has emerged as a prevalent phenomenon in the past decade, particularly for educational applications. This study's findings indicate that VR allows civil engineering students to engage with many environments, overcoming the limitations of real-world conditions and improving educational activities. Through immersive and interactive learning experiences, virtual reality cultivates vital 21st-century competencies, including critical thinking, teamwork, creativity, and technology literacy. The capacity to replicate intricate building environments without the hazards and constraints of physical site visits improves students' comprehension of academic and practical principles. Furthermore, the media generated in this work facilitates virtual access to building systems that would often necessitate an on-site visit for contextual examination. This tackles safety and logistical challenges while promoting collaborative problem-solving and innovative experimentation. As civil engineering education progressively incorporates digital technologies, virtual reality emerges as an essential instrument for equipping students to meet the requirements of Industry 4.0, where technology-driven solutions are critical. Nonetheless, issues in computer graphics may necessitate additional refining, encompassing the development of more intricate 3D objects and interactive components. Future research must analyze the long-term effectiveness of VR environments as learning tools and their impact on student outcomes across diverse engineering fields.

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