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Research paper

# Virtual Reality Prototype Development for Structural Learning in Bridge Engineering

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**ABSTRACT**

**Background:** The advancement of immersive technology such as Virtual Reality (VR) provides an opportunity to improve civil engineering learning by offering interactive 3D environments that support structural exploration. However, learning media based on VR for bridge engineering is still rarely developed and optimized in the academic field. This condition indicates the need for interactive digital media that strengthens conceptual understanding, spatial visualization, and practical interpretation of bridge structures.
**Methods:** This research employed a development approach using the 4D model (Define, Design, Develop, and Disseminate, limited only to the Develop stage). Evaluation was conducted through expert review involving material and media assessors to refine visual quality, navigation flow, and content presentation.
**Results:** The result of the development process is a functional VR prototype that allows users to explore bridge structures interactively. Users can observe components such as abutments, piers, girders, decks, and foundations from multiple perspectives, supported by information pop-ups that describe structural function and material characteristics. Expert feedback indicated that VR media has strong potential to enhance understanding of structural behavior and spatial configuration, and is considered feasible to be continued into the testing stage. Revisions focused on improving text readability, navigation control, texture sharpness, and instructional clarity.
**Conclusion:** The study demonstrates that VR-based learning media can serve as an innovative tool for bridge construction learning by bridging theoretical concepts with immersive visualization. The product developed in this study is ready for further implementation and effectiveness testing to evaluate student response and learning outcomes.

## INTRODUCTION

The advancement of digital technology has significantly transformed learning practices in higher education, particularly in engineering disciplines that require strong spatial reasoning and visualization skills. In civil engineering education, understanding structural systems is a fundamental competency because students are expected to interpret technical drawings, analyze structural behavior, and understand the relationships among construction components. However, learning bridge structures remains challenging because many concepts are presented through two-dimensional drawings, photographs, and textual descriptions that are often insufficient to represent the complexity of real-world structures.

Bridge Engineering is one of the courses that requires students to understand the geometry, function, and interaction of structural components such as foundations, abutments, piers, girders, decks, and bearings. Conventional learning approaches often rely on lectures, textbooks, and engineering drawings, which may limit students' ability to visualize structural configurations and construction processes comprehensively. As a result, students frequently encounter difficulties in developing spatial understanding and connecting theoretical concepts with actual bridge structures.

The development of educational technology has encouraged the adoption of immersive learning environments to address these limitations. Virtual Reality (VR) has been widely recognized as an emerging technology capable of creating realistic and interactive learning experiences that enhance visualization, engagement, and conceptual understanding (Freina & Ott, 2015; Mihelj et al., 2014). Through immersive virtual environments, learners can interact directly with digital objects and explore complex structures from multiple perspectives, enabling a deeper understanding of engineering concepts that are difficult to convey through conventional media.

Recent developments indicate that the role of VR in engineering and construction education continues to grow significantly. (C. Rodgers et al., 2026)reported that Virtual Reality has evolved into a primary medium for delivering complex content related to building systems and construction materials, improving students' spatial understanding and learning performance. This trend reflects the increasing need for instructional media capable of bridging the gap between theoretical knowledge and practical engineering applications. Recent implementation studies have also demonstrated the practical feasibility of integrating VR technology into civil engineering curricula, providing students with immersive learning experiences that complement conventional instructional approaches (C. J. Rodgers et al., 2025).

The implementation of VR is also aligned with the ongoing digital transformation within the architecture, engineering, and construction sectors. According to Abouelkhier et al., (2024), the integration of Virtual Reality and four-dimensional Building Information Modeling (4D BIM) provides valuable insights and strategic recommendations for improving construction management education in the digital era. The combination of immersive visualization and engineering information systems enables learners to better understand construction processes, project sequencing, and structural relationships within realistic environments.

As a pedagogical tool, VR supports experiential learning by allowing students to engage directly with virtual representations of engineering structures. Asad et al., (2021) emphasized that VR strengthens experiential learning by providing safe simulation environments where students can explore engineering systems and construction scenarios that may be difficult, expensive, or hazardous to access in real-life situations. Such learning environments encourage active participation, exploration, and knowledge construction through direct interaction with virtual objects.

The increasing adoption of VR in construction education has also been highlighted in recent scholarly reviews. Mastrolembo Ventura et al., (2022) found that the implementation of VR within construction-related education has increased substantially over the last decade. However, their findings also indicate that successful implementation requires systematic integration of instructional content to ensure alignment with civil engineering curricula and learning outcomes. Therefore, VR development should not only focus on technological sophistication but also on instructional design principles that effectively connect learning content with immersive visualization.

Several previous studies have demonstrated the effectiveness of VR in improving learning outcomes, increasing engagement, and enhancing students' understanding of technical concepts (Dharma et al., 2018; Putra & Aisyah, 2021). Nevertheless, the application of VR in bridge engineering education remains relatively limited. Most existing studies focus on general engineering visualization, construction safety training, or virtual learning environments without specifically addressing bridge structural learning. Furthermore, limited research has integrated visual design, instructional content, and technical implementation into a comprehensive development framework specifically designed for bridge engineering education.

In addition to providing immersive visualization, VR is closely related to the development of students' spatial visualization abilities, which are essential competencies in civil engineering education. Understanding bridge structures requires students to mentally interpret the relationships among structural components and transform two-dimensional representations into three-dimensional concepts. Tiwari & Bhagat, (2024)reported that spatial visualization is strongly influenced by web-based and markerless visualization approaches, which directly affect students' cognitive load when learning technical drawings. This finding highlights the importance of designing learning media that not only improve visualization but also support cognitive processing during engineering learning activities. Similar findings were reported by Darwish et al., (2023), who demonstrated that extended reality technologies can significantly enhance students' spatial abilities and improve their understanding of complex engineering and architectural designs.

The effectiveness of VR learning environments is also influenced by cognitive load considerations. While immersive technologies can enhance engagement and presence, excessive information complexity may hinder learning performance. Sari et al., (2024)emphasized that although immersive VR increases users' sense of presence, excessive cognitive load may reduce the effectiveness of learning materials. Therefore, instructional content integrated within VR environments should be carefully designed to balance immersion, interaction, and information delivery to ensure meaningful learning experiences.

From the perspective of experiential learning, VR enables students to gain learning experiences that closely resemble real-world situations without being constrained by safety, accessibility, or cost limitations. Previous studies have shown that immersive virtual environments provide opportunities for active exploration and direct interaction with engineering structures. Supporting this view, (Labib & Abdelsattar, 2025) found that virtual construction site visits produce learning outcomes comparable to those achieved through physical field visits in structural architecture courses. This indicates that VR can serve as an effective alternative learning medium when access to actual construction projects is limited.

The application of immersive technologies in bridge engineering education has also demonstrated promising results. Duan et al., (2024) reported that student-centered holographic learning paradigms supported by intelligent analytic hierarchy processes are highly effective in bridge engineering instruction. These findings suggest that immersive visualization technologies have significant potential to improve conceptual understanding, structural interpretation, and learning engagement in bridge-related subjects. Consequently, the development of VR-based learning media for Bridge Engineering courses represents a relevant and strategic effort to support the digital transformation of civil engineering education.

To address this gap, this study develops a Virtual Reality-based learning media prototype for Bridge Engineering courses using the ACE (Art, Content, and Engineering) approach integrated within the 4D development model. The Art component focuses on realistic three-dimensional visualization of bridge structures, the Content component emphasizes the integration of instructional materials through interactive hotspot-based learning, and the Engineering component ensures the technical functionality and usability of the VR environment. The novelty of this study lies in the integration of these three components within a single immersive learning environment designed specifically for bridge engineering education.

Therefore, this study aims to develop a Virtual Reality learning media prototype that facilitates the visualization of bridge structural components and supports students' conceptual understanding through immersive and interactive learning experiences. The resulting prototype is expected to serve as a foundation for future implementation, usability testing, and effectiveness evaluation in civil engineering education.

## METHODS

### Type of Research

This study applied a Research and Development (R&D) approach with the 4D development model (Define, Design, Develop, and Disseminate) introduced by (Thiagarajan et al., 1974).The model was selected because it provides a systematic framework for designing and producing educational media, particularly when the research focus emphasizes product development and improvement rather than implementation outcomes (Sugiyono, 2013; Borg & Gall, 1983). The objective of this research was to develop a Virtual Reality (VR)-based instructional media for bridge construction learning in civil engineering education. Considering the scope of this article, the research emphasizes the Develop stage, which includes prototyping, VR integration, and expert validation, without proceeding to dissemination and field trials. R&D is widely used in instructional technology development due to its structured stages that ensure quality improvement through iterative refinement.

Although the original 4D model consists of Define, Design, Develop, and Disseminate stages, this research was conducted only up to the Develop stage. The 4D model was selected because it provides a systematic framework for developing educational products through iterative design, validation, and refinement processes. Furthermore, the selection of Virtual Reality (VR) technology aligns with recent developments in construction education, where the integration of BIM and VR has been shown to create immersive learning environments that support the development of accurate and interactive learning media (Adhikari & Vadlamudi, 2025). Technology-driven educational innovation also requires structured development approaches to ensure accessibility, educational relevance, and effective implementation in digital learning environments (Zabala et al., 2026). The Disseminate stage was not implemented because the primary objective of this study was to develop and validate a functional VR prototype before large-scale implementation. In addition, dissemination activities require broader user involvement, institutional implementation, and effectiveness testing, which were beyond the scope and time frame of the current research. Therefore, the resulting prototype should be regarded as a preliminary product that is ready for further practicality testing, implementation, and dissemination in future studies.

The research procedure consisted of three main stages: Define, Design, and Develop. The Disseminate stage was not conducted in the present study. Information dissemination was limited to documentation, reporting, and academic publication of the development results. Broader dissemination through classroom implementation, institutional adoption, and large-scale evaluation is planned as a continuation of this research after practicality and effectiveness testing have been completed.

**Research Location and Time**

The research was conducted within the context of Civil Engineering Education, particularly during the development and refinement of VR instructional media for bridge construction material. Activities such as content collection, 3D object design, VR integration, and expert judgment were carried out throughout the designated research period stated in the thesis schedule. Validation and consultation sessions were conducted both in person and online to facilitate continuous feedback during product development.

**Research Subjects**

The research subjects consisted of one material expert and one media expert who were involved in evaluating the prototype during the development stage. The material expert assessed the accuracy, relevance, and suitability of bridge engineering content, while the media expert evaluated visual quality, navigation systems, user interaction, and technical functionality of the VR application. Student users were not involved during the current phase because this study focused on prototype development and expert validation prior to implementation. User involvement was intentionally postponed until the subsequent stage of research, where practicality testing, usability assessment, and effectiveness evaluation will be conducted. Therefore, the current study emphasizes formative evaluation through expert judgment to ensure that the prototype meets pedagogical and technical requirements before being tested by students.

The independent variable in this study was the development process of VR learning media using the ACE (Art, Content, and Engineering) framework. The Art component included 3D modeling, texture design, lighting, and visual presentation. The Content component included instructional materials, bridge structure descriptions, learning objectives, and hotspot-based information delivery. The Engineering component involved VR integration, navigation systems, interaction programming, optimization processes, and system functionality within the virtual environment.

The dependent variable was the quality of the VR learning media prototype. Media quality was operationally defined through indicators of content suitability, visual presentation quality, navigation performance, interactivity, usability, and feasibility for learning purposes. These indicators were evaluated through expert reviews and prototype assessment during the development process.

The measurement of the dependent variable was conducted through expert evaluation using structured review guidelines. Material experts assessed content accuracy, relevance, and instructional appropriateness, while media experts evaluated interface design, visual quality, interaction mechanisms, and navigation performance. Because the present study was limited to the prototype development phase, usability testing involving students was not conducted. User-based measurements such as the System Usability Scale (SUS) are recommended for future studies when the prototype proceeds to implementation and practicality testing stages.

**Data Analysis Techniques**

Data were analyzed descriptively through documentation of the development process, expert review results, revision notes, and prototype evaluation. The analysis focused on describing media feasibility, content suitability, navigation performance, and the overall quality of the VR application during development. Statistical testing or learner-based trials were not performed, as the scope of this article is limited to the development stage without implementation testing.

## RESULTS AND DISCUSSION

The development of the Virtual Reality (VR) learning media for bridge construction was executed systematically following the 4D development model that had been predetermined in the research design. All activities progressed according to the plan outlined in the thesis, beginning with the identification of required learning materials, development of 3D structural models, user interface design, integration within the VR platform, and subsequent expert review. The sequential process of development demonstrated that VR technology is capable of bringing bridge structure concepts into a more immersive and interactive learning space, which is difficult to achieve using conventional 2D media. The visualization of structural details in VR allows users to observe the object spatially, rotate perspectives, and view elements closely, supporting a deeper understanding of structural mechanisms and component relationships. This step-by-step creation confirmed the feasibility of VR as a supportive medium in civil engineering learning, especially in structural-related subjects like bridge construction, which highly rely on visualization.

**1. Define Stage: Material and Needs Identification**

In the initial stage, a needs analysis was conducted based on curriculum review, competency standards, lecturer interviews, and observation of student learning challenges. The results indicated that many students experience difficulties in interpreting technical drawings and understanding spatial forms of bridge elements, especially when learning is dominated by 2D representations. Therefore, the study identified primary construction elements such as foundations, abutments, piers, girders, diaphragms, and deck slabs as key visuals that needed to be included in the VR media. Structural references and guidelines were also collected to ensure that the virtual representation followed civil engineering specifications. This stage served as the foundation for further design decisions and ensured that the final product remained relevant to learning objectives.

**Table 1.**
Adjustment of Learning Materials in Bridge VR Media

| Learning Materials | Presentation Format in VR | Learning Objectives |
|---|---|---|
| Types of Bridges | Interactive 3D models of several bridge types (suspension, truss, concrete, arch, and cable-stayed) | To understand the characteristics, functions, and differences in application of each bridge type |
| Bridge Components | Detailed structural section models equipped with labels and functional descriptions | To identify structural components such as piers, abutments, deck, girders, cables, and foundations |
| Construction Process | Animated simulation of construction stages presented sequentially | To observe how bridge construction is carried out from the initial stage to completion |
| Project Case Study | Real bridge model used as a field reference | To connect theoretical concepts with actual implementation in infrastructure projects |

**2. Design Stage: Storyboard, 3D Concept, and Interface Layout**

In the design stage, the conceptual blueprint of the learning media was developed. The research team created a storyboard and organized the flow of the virtual environment, defining how users would enter the scene, interact with hotspot points, and navigate the structure. The placement of the structural components was arranged to mimic realistic bridge construction order, allowing learners to move around the deck, observe the pier and abutment, and even move beneath the structure. Clickable icons were designed as hotspots that display material explanations when interacted with. This stage also determined the use of first-person navigation to create a sense of presence, immersion, and direct exploration. Thus, students can experience the structure as if visiting a real bridge site rather than viewing static illustrations (Figure 1).

**3. Develop Stage (Primary Stage of This Study)**

The develop stage was the core of the research, where the learning media began to take shape as a functional prototype. The modeling process was carried out using 3D development software, where each component of the bridge was constructed with proportional dimensioning based on engineering references. Foundations and abutments were modeled first, followed by the pier, girders, deck surface, and additional components such as barrier railings. Texturing was applied using material presets that represented concrete, steel, and asphalt, while lighting and shadow adjustments were made to enhance realism. After the visual model was completed, the entire structure was exported and integrated into the VR platform. Interaction features such as viewpoint movement, camera rotation, and teleports were activated, enabling users to freely explore the environment. At this stage, the media had already reached the form of a preliminary VR prototype (Figure 2).

**4. Integration of Learning Materials into VR Scene**

Learning content was embedded into the VR scene in the form of interactive information hotspots placed strategically on each structural component. When users point or click on these hotspots, explanatory text will appear containing brief descriptions of component roles, structural function, load transfer mechanism, material specifications, and inspection relevance. This design allows theoretical information to be accessed directly beside the visual object, supporting simultaneous cognitive processing between conceptual and visual inputs.

The use of VR in this stage is expected to improve comprehension by reducing abstraction and enabling real-time situational interpretation. Students can visually compare how girders support loads or how abutments transfer forces to the ground, an experience difficult to acquire using textbooks or drawings alone (Figure 3).

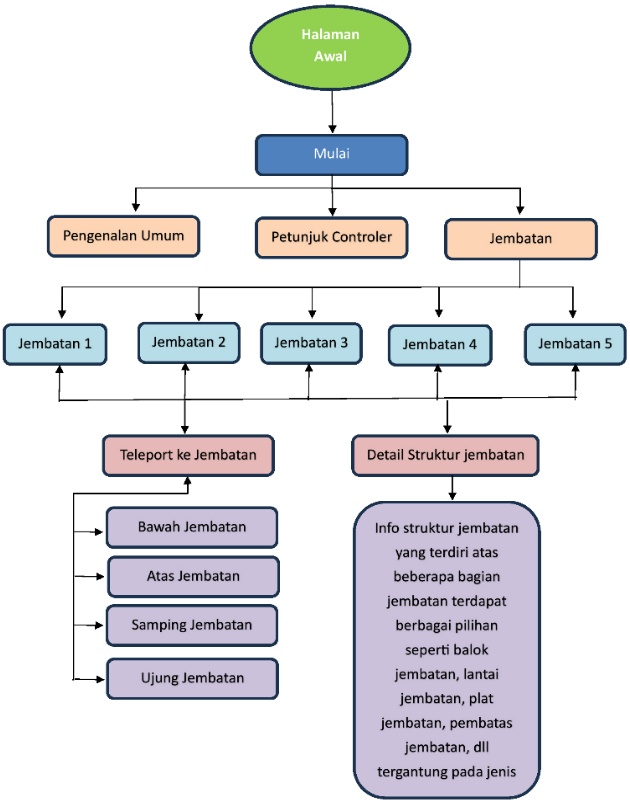


**Figure 1**. Flowchart VR Bridge

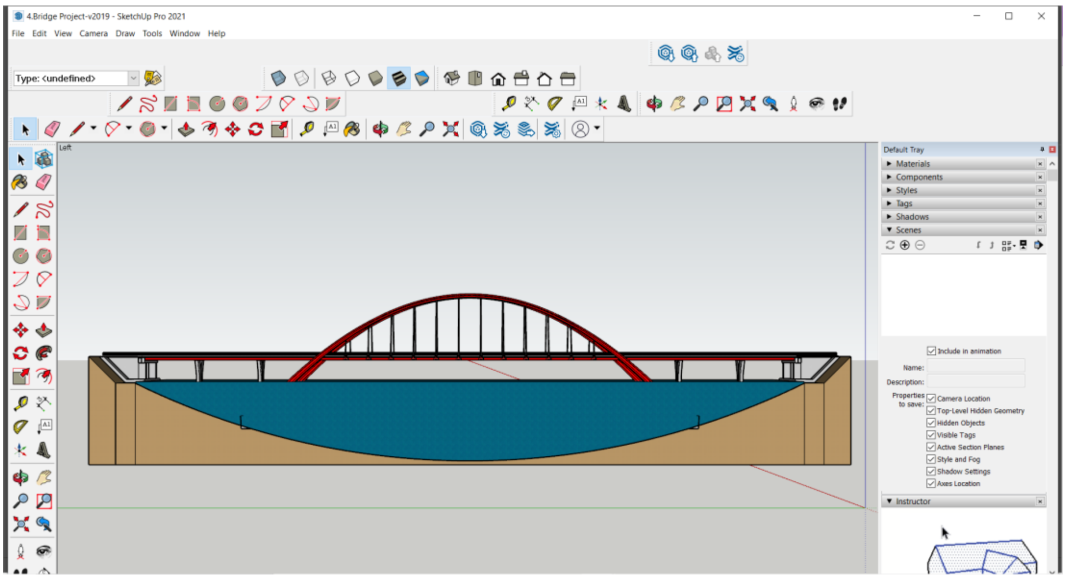


**Figure 2**. Development of Bridge Model in 3D Environment


**Figure 3**. Hotspot-Based Content Interaction in VR

**5. Expert Review and Prototype Refinement**

Before progressing to the implementation phase, the VR prototype underwent evaluation by material and media experts. The material expert assessed the accuracy of content, naming conventions, and relevance of explanations based on civil engineering standards. Meanwhile, the media expert evaluated visual sharpness, navigation fluidity, interface clarity, and overall user experience. Several improvements were suggested during this stage, such as enhancing texture quality, adjusting navigation speed, optimizing lighting for better visualization, and improving text readability. The inclusion of an introductory guide was also recommended to help new users navigate the VR environment more easily. After revisions were implemented, the product reached a ready-to-test prototype stage meeting the criteria for further practicality and effectiveness assessment in future research.

**6. Evaluation and Feedback**

The evaluation stage in this development process was carried out after the VR prototype was completed through the Define, Design, and Develop stages. Evaluation was conducted through open discussions and expert review sessions involving a material expert and a media expert. Through this forum, evaluators provided feedback on the clarity of the visual elements, accuracy of structural content, navigation flow, and the effectiveness of information delivery through the interactive hotspots. In addition, reviewers assessed the suitability of terminology used within the VR environment to ensure alignment with engineering standards and learning outcomes. The feedback obtained at this stage helped the developer identify aspects that required refinement, including text readability, interface responsiveness, and additional explanations for several bridge components to ensure comprehensive conceptual understanding (Mihelj et al., 2014). This stage also provided an opportunity to detect minor technical issues that may hinder user experience if not addressed early.

Based on this review, several recommendations for improvement were formulated. These included enhancing texture clarity on 3D elements, adjusting navigation sensitivity for smoother movement, adding introductory user instructions within the VR interface, and refining the placement of information nodes for better accessibility during exploration. Experts also suggested including more detailed structural behaviour descriptions to strengthen the learning experience. Additional suggestions involved optimizing lighting intensity to reduce visual fatigue and providing optional audio narration for future versions to support multimodal learning. These recommendations are aligned with the principle that digital instructional media must meet standards of usability, clarity, and accessibility (Munadi, 2019). The suggestions will be implemented in the next development cycle prior to field testing to ensure that the product meets pedagogical expectations and is ready for student use.

Overall, the evaluation and feedback process showed that the VR media prototype was technically functional and conceptually relevant for bridge construction learning. The immersive visualization of structural elements such as abutments, piers, girders, and decks was assessed to have strong potential to improve student comprehension in terms of spatial understanding. The interactive hotspot feature was also considered effective in delivering explanations, as users could directly relate conceptual material to visual models. This aligns with studies suggesting that virtual and 3D-based instruction increases cognitive engagement and material retention (Freina & Ott, 2015). Furthermore, the flexibility for users to explore components from different angles was viewed as an added value that may encourage self-directed learning. Although student implementation has not been conducted, expert judgment indicates that the VR prototype has strong learning potential and could support classroom activities as supplementary digital media.

The findings of this study indicate that the developed VR prototype has the potential to support bridge engineering learning through immersive visualization and interactive exploration of structural components. The positive evaluation obtained from expert validation suggests that the prototype provides an appropriate foundation for future implementation and user testing. These findings are consistent with previous studies that have demonstrated the educational value of immersive technologies in engineering education.

Try et al., (2021)reported that VR applications used as instructional support tools in civil engineering laboratories demonstrated advantages over conventional learning methods in multicriteria comparative evaluations. Similarly, the developed prototype in this study was designed to provide students with opportunities to observe and explore bridge structural components in ways that are difficult to achieve through traditional two-dimensional learning materials. This result is also consistent with the findings of Sahbaz, (2021), who demonstrated that VR-based construction studio simulators can provide realistic learning environments that facilitate interactive exploration and improve students' engagement in construction-related learning activities.

The present findings are also aligned with the work of Alizadehsalehi et al., (2021), who found that the integration of Building Information Modeling (BIM) within VR environments significantly improved technical understanding among Architecture, Engineering, and Construction (AEC) students. Although the current study did not evaluate learning effectiveness directly, the integration of realistic three-dimensional visualization and instructional content within the VR environment is expected to support conceptual understanding of bridge structures in a similar manner.

Furthermore, Han (2021) found that students perceived immersive virtual field trips as effective alternatives for overcoming geographical and logistical constraints when learning about construction structures and engineering projects. This perspective is particularly relevant to bridge engineering education, where direct access to bridge construction sites or structural inspections may be limited by safety, distance, and operational considerations. Therefore, the developed VR prototype offers a promising alternative for providing students with realistic structural learning experiences within a controlled virtual environment.

In conclusion, the feedback stage significantly contributed to improving the quality of the VR learning media. The expert input served as a basis for refining visualization aspects, navigation control, and instructional information. These findings support the idea that development models such as 4D require iterative validation to produce a ready-to-test product (Thiagarajan et al., 1974). With continued refinement, the VR media is expected to enhance conceptual understanding and visualization in bridge construction education. The product demonstrates the potential of VR technology to create interactive, realistic, and engaging learning environments in civil engineering domains. In future development, user trials involving students are recommended to evaluate practicality, engagement, and effectiveness, ensuring that the media is not only technically feasible but also pedagogically impactful.

This study has several limitations. First, the developed product remains at the prototype stage and has not yet been implemented in actual classroom learning. Second, student users were not involved in usability and effectiveness testing because the study focused on development and expert validation. Third, the Disseminate stage of the 4D model was not conducted, limiting the evaluation of broader implementation and adoption. Consequently, conclusions regarding learning effectiveness, student engagement, and long-term educational impact cannot yet be established. Future research should involve student-based usability testing, experimental learning evaluation, and wider dissemination to validate the educational effectiveness of the developed VR media.

## CONCLUSION

This study aimed to develop a Virtual Reality (VR)-based learning media prototype for Bridge Engineering courses using the 4D development model to support students' understanding of bridge structural components through immersive and interactive visualization. The development process focused on creating a functional VR environment that integrates three-dimensional bridge models, hotspot-based instructional content, and interactive navigation features to facilitate structural exploration and conceptual learning.

The results indicate that the developed VR prototype successfully visualizes major bridge components, including abutments, piers, girders, decks, and foundations within an interactive virtual environment. Through the Define, Design, and Develop stages, the prototype was designed to address learning difficulties related to spatial visualization and the interpretation of conventional two-dimensional representations commonly encountered in bridge engineering education. Expert evaluation further confirmed that the prototype possesses adequate content relevance, visual quality, and technical functionality to proceed to subsequent testing stages.

This study also demonstrates the potential of integrating the ACE (Art, Content, and Engineering) approach into VR learning media development. The integration of realistic 3D visualization, instructional content, and VR system engineering provides a foundation for more immersive and meaningful learning experiences in civil engineering education. Therefore, the developed prototype may serve as an alternative instructional medium to support conceptual understanding and structural visualization in bridge engineering courses.

However, the present study is limited to the development and expert validation stages. User testing involving students, practicality assessment, and effectiveness evaluation have not yet been conducted. Future research should continue with implementation, usability testing, and learning outcome evaluation to determine the educational impact of the developed VR media. Additional features such as construction sequence simulation, structural behavior visualization, and assessment integration are also recommended to further enhance the learning experience and instructional effectiveness.

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## DISCLOSURE STATEMENT

The authors declare that there is no potential conflict of interest regarding the conduct of this research, the preparation of the manuscript, or the publication process.

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