Immersive Virtual Reality in Geoscience Education: Effects on Conceptual Understanding, Spatial Reasoning, and Student Engagement

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ABSTRACT

Virtual Reality (VR) has the potential to enhance geoscience education by enabling students to explore subsurface processes that are difficult to visualise using conventional teaching methods. This study describes the development and classroom implementation of an immersive VR learning module focused on geomechanics topics such as stress–strain behaviour, elastic deformation, and pore–fluid interactions, using Malaysian reservoir contexts. The study employed a one-group pre–post instructional design involving 40 final-year petroleum geoscience students at Universiti Teknologi PETRONAS. Data were collected through conceptual assessments administered before and after the VR session, a post-activity Likert-scale questionnaire, and short written reflections. Quantitative data were analysed using descriptive statistics, while qualitative responses were examined thematically. The results indicate high levels of student engagement and enjoyment, strong preference for VR-based learning compared to traditional lectures, and noticeable improvements in spatial understanding of geomechanics concepts. These findings suggest that immersive VR can serve as an effective complementary approach for supporting conceptual learning and student motivation in higher-education geoscience programmes.

Keywords
Virtual reality; Geosciences education; Immersive learning; Student engagement; Spatial visualisation

Introduction

Geomechanics is one of the important subjects in the undergraduate geoscience programme at UTP. Visualising the subsurface behaviour which cannot be observed in real time, is a crucial way to truly understand the concepts in this subject (Gao & Zhou, 2025). Some of the concepts are mainly introduced via equations, graphs and 2D diagrams such as stress-strain relationship, elastic deformation, pore connectivity and fluid migration (Bouchez & Nicolas, 2021). With these types of introductory methods, the students are provided with crucial theoretical foundations but often fall short in building strong spatial intuition (Ishikawa & Newcombe, 2021). This makes interpreting real reservoir conditions and making informed decisions very challenging in the energy industry later on.

Virtual reality (VR) offers a promising pathway to address these limitations. VR enables direct interaction with geological structures and behaviours that are otherwise abstract or physically inaccessible by creating an immersive three-dimensional environment (Tibaldi et al., 2020). Most of the recent advances in VR technology have enabled its use in broad settings such as engineering classrooms which shows the potential in improving spatial reasoning and knowledge retention (Chasokela, 2025). For the disciplines such as petroleum geoscience, where understanding rock deformation and fluid flow is fundamental VR can help in bridging the gap between theoretical models and practical interpretation (Mota et al., 2025).

Recognising these opportunities, a VR learning module was developed at Universiti Teknologi PETRONAS (UTP) to support final-year petroleum geoscience students in mastering key geomechanics concepts. The module simulates rock behaviour under different stress conditions, visualises elastic and plastic responses, and illustrates variations in porosity and permeability through fluid-flow scenarios grounded in Malaysian reservoir characteristics. Unlike conventional instruction, the VR experience allows students to manipulate forces, rotate rock models, observe deformation instantaneously, and explore pore networks from multiple viewpoints (Abdullah & Olorode, 2025).

This study presents the development and classroom implementation of the VR module, along with students' responses after using it during a geomechanics laboratory session. The work aims to demonstrate how VR can enhance conceptual understanding, increase engagement, and make complex Geomechanical principles more accessible. By documenting students' enjoyment and perceived learning improvements, this paper contributes to ongoing discussions on technology-enhanced learning and provides evidence supporting the integration of immersive tools in higher-education geoscience curricula (Klippel et al., 2019).

Literature Review

Teaching geoscience has long required students to conceptualise processes that occur deep beneath the Earth's surface (Conrad & Libarkin, 2022). These processes cannot be directly observed, yet they are fundamental to understanding reservoir behaviour and subsurface systems (Willis et al., 2021). As a result, geoscience education has traditionally relied on diagrams, textbook illustrations, mathematical formulations, and limited laboratory demonstrations to convey complex ideas (Locke et al., 2012). While these methods provide essential theoretical foundations, they often struggle to communicate the true scale, geometry, and dynamic relationships that characterise geological systems (Cox et al., 2020). Consequently, students may become familiar with definitions of stress, strain, porosity, or permeability without fully understanding how these concepts interact within real subsurface environments (Campa-Bousoño & García-Pérez, 2025).

One of the key challenges in geoscience education lies in the abstraction required to translate two-dimensional representations into three-dimensional mental models. Static figures and equations demand a high level of spatial reasoning, which not all learners develop at the same pace (Liben et al., 2011). This can lead to gaps between theoretical knowledge and applied understanding, particularly in advanced topics such as rock deformation, fracture behaviour, and fluid migration (Gagnier et al., 2017). For students preparing for professional roles in the energy sector, these gaps may hinder their ability to interpret reservoir data and make informed decisions (Jimenez-Martinez, 2023).

Virtual Reality (VR) has gained increasing attention as a tool capable of addressing these limitations by bridging the gap between theory and intuition (Aruanno et al., 2025). VR enables learners to enter immersive three-dimensional environments where geological structures, deformation processes, and fluid behaviour can be explored interactively (Yang et al., 2024). Instead of imagining how a rock responds to applied stress, students can observe deformation as it occurs. Rather than visualising pore networks abstractly, learners can follow fluid pathways as they move through connected spaces. This shift from abstract explanation to experiential learning has positioned VR as a promising approach within science and engineering education (Aruanno et al., 2025).

Immersive Learning in Geoscience

The growing interest in immersive learning stems from the recognition that many geoscience concepts rely heavily on spatial understanding (Bagher et al., 2020). Conventional instructional approaches often depend on static visuals that limit students' ability to perceive depth, movement, and temporal change (Castro-Alonso et al., 2019). Immersive environments address this challenge by introducing interactivity, allowing learners to engage with models dynamically rather than passively observing representations (Bagher et al., 2023).

Research across STEM disciplines suggests that immersive learning environments can enhance student motivation, sustain attention, and encourage active participation (Guerra et al., 2024). In geoscience education, these benefits are particularly valuable because learners must integrate multiple variables such as stress orientation, material properties, and fluid behaviour within a single conceptual framework. VR allows these elements to be examined simultaneously, supporting the construction of more coherent mental models (Abdul Latiff & Jiménez, 2024). By reducing the cognitive burden associated with mental reconstruction, immersive learning environments can make complex concepts more accessible, especially for students who struggle with abstract visualisation (Xu, 2025).

Beyond cognitive benefits, immersive learning has also been associated with positive affective outcomes (Nikou, 2025). Students often report higher levels of interest and enjoyment when learning activities involve interaction and exploration. These affective responses are important, as motivation and engagement influence how deeply students process information and how persistently they approach challenging material (Izouaouen et al., 2025). In demanding subjects such as geomechanics, the ability of VR to foster curiosity and sustained engagement may contribute meaningfully to learning outcomes. These findings provide a clear rationale for examining immersive VR as a learning approach in the present study, particularly for supporting conceptual understanding, spatial reasoning, and student engagement in geomechanics education.

VR Applications in Geomechanics and Reservoir Studies

While VR has been used for virtual field trips and seismic interpretation, its adoption in geomechanics is more recent (García-Vela et al., 2021). Yet the potential is significant. Geomechanical behaviour such as rock deformation, fracture development, or changes in permeability can be difficult to grasp from equations alone (Beer & Opriessnig, 2018). VR offers a unique way to demonstrate these phenomena by allowing students to manipulate virtual samples, apply forces, or observe how pores connect and disconnect under different conditions.

VR-based geoscience tools often emphasise several strengths:

1. Improved visual clarity: Students can see deformation or fluid movement in real time rather than relying on imagination.
2. Interactive learning: Users can rotate, pull, compress, or stretch rock models, making the experience hands-on instead of passive.
3. Safe experimentation: Extreme pressure scenarios or unrealistic fluid injections can be simulated without any physical risk.
4. Higher engagement: The immersive nature of VR tends to capture students' attention more effectively than lecture slides.

For final-year geoscience students, these advantages are especially relevant because they are preparing for industry roles where interpreting real reservoir data requires strong conceptual understanding (Abdul Latiff & Jiménez, 2024). Another advantage of VR in geomechanics education is the ability to simulate extreme or impractical scenarios safely. High-pressure conditions, large-scale deformation, or accelerated fluid flow can be visualised without physical risk or resource constraints (Isleyen & Duzgun, 2019). Furthermore, the immersive nature of VR has been shown to capture students' attention more effectively than traditional lecture materials, potentially leading to greater engagement during learning activities (Lawton et al., 2024).

Gaps in Current Research

Despite the growing interest in VR as an educational tool, several gaps remain in the existing literature. Many studies focus primarily on technological development rather than examining how students experience and respond to VR-based learning in authentic classroom settings (Izouaouen et al., 2025). In some cases, evaluations are limited to short demonstrations or pilot activities, making it difficult to assess sustained learning impact (Mota et al., 2025).

Additionally, affective outcomes such as enjoyment, confidence, and learning motivation are often underexplored, despite their importance in supporting meaningful learning (Chasokela, 2025). There is also a lack of context-specific VR content, with many applications relying on generic geological models that may not reflect the regional characteristics familiar to students (Yang et al., 2024). Learning materials that incorporate local geological settings may enhance relevance and support stronger connections between theory and real-world application (Locke et al., 2012).

These gaps highlight the need for studies that examine both cognitive and experiential outcomes of VR integration within structured geoscience courses. Investigating how students perceive, engage with, and benefit from VR-based learning activities can provide valuable insights into the effective use of immersive technologies in higher education geoscience programmes.

Research Objectives

The research objectives of this research are:

1. To identify the extent to which a Virtual Reality (VR) module enhances students' understanding of key geomechanics concepts, including stress–strain behaviour, elastic moduli, and pore–fluid interactions.
2. To explore students' levels of enjoyment, engagement, and preference when using VR compared to traditional lecture-based instruction.
3. To analyse students' perceived improvements in spatial reasoning and conceptual clarity after interacting with the VR simulations.

Methods

This study employed an educational implementation approach to examine the use of an immersive Virtual Reality (VR) learning activity within undergraduate geoscience education (Mota et al., 2025). The methodological focus was placed on teaching practice, student learning development, and learner experience rather than on the technical performance or system optimization of the VR application. This approach emphasises innovation in teaching and learning and its impact on student engagement and understanding. The VR learning activity was integrated into a scheduled geomechanics laboratory session for final-year petroleum geoscience students. Embedding the activity within an existing course structure ensured that learning took place under authentic instructional conditions and reflected real classroom practice. This allowed the study to examine how VR functions as a supplementary teaching tool rather than as a stand-alone intervention.

The VR content focused on geomechanics concepts that students typically find challenging due to their abstract and spatial nature, including rock deformation behaviour, stress–strain response, and fluid movement within porous media (Shi et al., 2022). These concepts were represented through interactive three-dimensional models that students could observe, rotate, and explore. The learning activity was designed to support visual understanding and intuitive exploration, allowing students to connect theoretical ideas introduced in lectures with observable subsurface behaviour.

At the beginning of the laboratory session, students were provided with a brief orientation outlining the learning objectives and basic interaction methods within the VR environment. The instructor facilitated the session by guiding students through the activity while encouraging independent exploration and peer discussion. This instructional approach aimed to balance structure and autonomy, enabling students to actively engage with the learning material without feeling overwhelmed by unfamiliar technology (Anand, 2024). Data collection was conducted during and immediately after the VR learning session using multiple sources to capture both learning outcomes and student experiences. Conceptual assessments, questionnaires, and written reflections were used to provide a comprehensive view of how the teaching innovation influenced student learning and engagement (Ogunfunmi et al., 2014).

Research Design

The study adopted a mixed-methods research design, combining quantitative measures of learning outcomes with qualitative analysis of student reflections. Specifically, a one-group pre–post instructional design was used to examine changes in students' conceptual understanding following participation in a VR learning activity, while qualitative data were collected to capture students' perceptions and learning experiences (Castro-Alonso et al., 2019). This approach was selected to provide both measurable evidence of learning change and deeper insight into how students experienced and interpreted the VR-based instruction.

The design prioritised instructional relevance and reflective evaluation rather than experimental comparison. The research design consisted of three main instructional stages. First, students completed a pre-assessment to establish their baseline understanding of selected geomechanics concepts. This assessment provided insight into students' initial conceptual clarity prior to exposure to the VR learning activity. Second, students participated in a guided VR learning session during the laboratory class. During this stage, students interacted with the VR environment, explored subsurface models, and observed changes in rock behaviour and fluid movement. The instructor facilitated discussion and prompted students to relate visual observations to previously learned theory. The final stage involved a post-assessment and a structured questionnaire administered immediately after the VR session. The post-assessment was used to examine changes in conceptual understanding, while the questionnaire and written reflections focused on enjoyment, engagement, perceived clarity, and learning preferences. This sequence allowed the study to capture both cognitive development and affective responses within a single instructional cycle.

Samples and Population

The participants in this study were forty final-year undergraduate students enrolled in a petroleum geoscience programme at Universiti Teknologi PETRONAS. These students were selected based on their enrolment in a geomechanics-related course in which the VR learning activity was embedded. All participants had previously completed coursework involving traditional geomechanics instruction, including lectures, diagrams, and standard laboratory exercises. None of the participants had prior experience using immersive VR as part of their formal geoscience education. This ensured that student responses reflected an initial encounter with VR-supported learning rather than familiarity with the technology. The cohort represented a typical group of senior undergraduate students preparing for industry-related roles that require strong conceptual and spatial understanding of subsurface processes. Participation in the study was voluntary, and students were informed that their responses would be used solely for research and teaching improvement purposes. All data were anonymised prior to analysis to ensure confidentiality and ethical compliance.

Research Instruments

Several instruments were used to collect data related to student learning and experience. Conceptual understanding was measured using a short assessment administered before and after the VR learning session. The assessment focused on conceptual interpretation rather than numerical problem-solving. It included questions related to deformation behaviour, stress response, and fluid–rock interaction. Using the same assessment structure at both stages allowed changes in understanding to be examined directly. The assessment items were developed based on course learning outcomes and reviewed by subject-matter experts in geomechanics to ensure content relevance and clarity. Minor refinements to wording were made following this review to improve interpretability. This process helped support the content validity of the instrument.

Students' learning experiences were examined using a structured questionnaire administered after the VR session. The questionnaire employed a five-point Likert scale ranging from strongly disagree (1) to strongly agree (5) and focused on enjoyment, engagement, perceived clarity of complex concepts, and overall learning preference. The questionnaire items were adapted from established measurement scale including the Intrinsic Motivation Inventory (Ostrow & Heffernan, 2018) and the Student Course Engagement Questionnaire (SCEQ) ((Handelsman et al., 2005), with wording adjusted to reflect immersive VR context in geomechanics learning. Prior to full deployment, the questionnaire was pilot tested informally with a small group of students to confirm clarity and ease of interpretation, resulting in a Cronbach's alpha value of 0.89, which indicates strong internal consistency (Cortina, 1993). In addition to structured responses, students were invited to provide brief written reflections describing their experience of the VR learning activity. These reflections allowed students to articulate their thoughts in their own words and provided qualitative insight into how the VR activity influenced their understanding and motivation.

Data Analysis

Quantitative data collected from both the pre-assessment and post-assessment were systematically analysed using descriptive statistical techniques to investigate shifts in students' conceptual understanding after participating in the VR-based learning activity. Key metrics, including mean scores and percentage differences between pre- and post-assessment results, were calculated to provide a clear and comprehensive picture of students' learning progression (Harbison & Simmons, 2024). These statistics offered an initial, objective measure of the effectiveness of the VR intervention in enhancing knowledge acquisition. In addition to test scores, responses from the structured questionnaires were examined to capture students' perceptions of the learning experience. Levels of agreement across individual questionnaire items were reviewed to detect patterns related to enjoyment, engagement, motivation, and perceived educational value. This analysis helped identify which aspects of the VR experience students found most impactful, highlighting both strengths and areas for potential improvement.

To complement the quantitative findings, qualitative data derived from students' written reflections were subjected to a thematic analysis. Responses were carefully read multiple times to ensure a deep understanding of recurring concepts and insights. Prominent themes that emerged included enhanced visualisation of complex concepts, the interactive nature of VR, levels of engagement and enjoyment, and improvements in comprehension. These qualitative insights provided rich contextual evidence that helped explain the patterns observed in the numerical data (Shaughnessy et al., 2017). By integrating both quantitative and qualitative approaches, the study aimed to deliver a nuanced and practical evaluation of the VR learning intervention. This mixed-methods approach allowed for a thorough assessment of not only the measurable learning gains but also the experiential aspects of the classroom implementation, offering valuable implications for future applications of VR technology in educational settings.

Results

This section reports the outcomes of the VR learning implementation by presenting changes in students' conceptual understanding, levels of engagement and enjoyment, perceptions of key VR features, and qualitative feedback from student reflections. The results are organised to provide a clear description of the evidence collected during and after the VR learning activity.

Changes in Conceptual Understanding

Students' understanding of selected geomechanics concepts was assessed before and after participation in the VR learning session. Table 1 presents the mean pre-test and post-test scores, along with the percentage improvement for each assessment area.

As shown in Table 1, increases in mean scores were observed across all assessed concepts following the VR activity. Stress–strain interpretation and fluid flow and permeability concepts recorded the largest gains, each showing a 24% improvement. Understanding of elastic versus plastic deformation improved by 23%, while porosity and pore connectivity showed a 22% increase. Overall, the average score rose from 57% in the pre-assessment to 79% in the post-assessment, reflecting a consistent upward shift in conceptual performance.

Table 1
Pre–Post Conceptual Understanding Scores (n = 40)

Assessment Item	Pre-Test Mean (%)	Post-Test Mean (%)	Improvement (%)
Stress–Strain Interpretation	54	78	+24
Elastic vs. Plastic Deformation	58	81	+23
Porosity & Pore Connectivity	60	82	+22
Fluid Flow & Permeability Concepts	55	79	+24
Overall Average	57	79	+22

Student Engagement and Enjoyment Levels

Students' engagement and enjoyment were measured using a structured questionnaire administered after the VR session. Table 2 summarises the proportion of students who agreed or strongly agreed with statements related to their learning experience.

The data in Table 2 indicate high levels of positive responses across all survey dimensions. Most students reported that the VR activity was highly engaging (92%) and expressed a preference for VR-based learning compared to traditional lectures (88%). High levels of agreement were also observed for statements related to improved conceptual clarity (90%), increased learning motivation (89%), and enhanced confidence in geomechanics (87%).

Table 2
Student Enjoyment and Engagement Levels

Survey Dimension	% Agree / Strongly Agree
VR activity was highly engaging	92%
VR preferred over traditional lectures	88%
VR made concepts clearer	90%
VR increased learning motivation	89%
VR boosted confidence in geomechanics	87%

Perceptions of VR Learning Features

To capture students' views on specific aspects of the VR environment, participants evaluated several features related to usability and instructional value. The overall response trends for each feature are presented in Table 3.

According to Table 3, students responded very positively to the visual clarity of subsurface models and the usefulness of VR for understanding theoretical concepts. The realism of the deformation simulations also received high ratings. Navigation within the VR environment and its usefulness for exam preparation were rated positively, with responses ranging from moderate to high across the cohort.

Table 3
Student Perceptions of VR Features

Assessment Item	Response Trend (n = 40)
Visual clarity of subsurface models	Very Positive (High)
Ease of navigating VR environment	Positive (Moderate–High)
Usefulness for understanding theory	Very Positive (High)
Realism of deformation simulations	Positive (High)
Helpful for exam preparation	Moderate–High

Qualitative Themes from Student Reflections

In addition to quantitative measures, students provided short written reflections describing their experiences during the VR learning activity. These responses were analysed to identify recurring themes, which are summarised in Table 4 along with representative paraphrased examples.

As summarised in Table 4, the most frequently reported themes included improved visualisation of subsurface processes, a strong sense of immersion, and clearer understanding of complex concepts. Several students also mentioned increased motivation and expressed interest in seeing VR integrated into other geoscience courses. These qualitative observations provide descriptive insight into students' experiences during the VR session.

Table 4
Summary of Qualitative Themes from Student Reflections

Theme Identified	Frequency	Example Student Statement (Paraphrased)
Visualisation improvement	High	"I could finally see how pores connect."
Immersive learning experience	High	"It felt like doing a lab inside VR."
Increased motivation	Medium	"This made geomechanics more interesting."
Better conceptual clarity	High	"Deformation made sense after seeing it happening."
Desire for more VR in courses	Moderate–High	"I want VR in other geology subjects."

Summary of Key Outcome Indicators

To provide an overview of the main quantitative findings, Table 5 consolidates key indicators related to participation, engagement, learning preferences, and conceptual improvement.

Table 5 shows that the study involved 40 participants and recorded high engagement and enjoyment levels. Strong preference for VR over lectures, perceived improvement in conceptual clarity, increased confidence, and an overall conceptual score improvement of 22% are also evident. This summary highlights the overall pattern of student responses observed following the VR implementation.

Table 5
Summary of Key Result Indicators

Metric	Value
Number of participants	40
Engagement rating	92%
VR preference over lectures	88%
Concept clarity improvement	90%
Confidence gain	87%
Overall conceptual score improvement	+22%

Taken together, the results demonstrate consistent patterns across assessment scores, questionnaire responses, and qualitative feedback. The findings presented in this section describe students' learning outcomes and experiences following the VR activity and provide a factual basis for the discussion in the subsequent section.

Discussions

The results of this study show that the VR learning module made a clear difference in how students understood and interacted with geomechanics concepts. The improvement observed in the pre–post assessments indicates that many students gained a stronger grasp of stress–strain behaviour, deformation processes, and pore–fluid interactions after exploring these ideas in an immersive 3D environment. These topics are typically hard to visualise from diagrams alone, so it is not surprising that students benefited from being able to manipulate rock models and observe changes directly. The 22% overall increase in conceptual scores suggests that VR helped turn abstract ideas into something more concrete and accessible.

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Beyond cognitive gains, the affective responses highlight an important dimension of VR-based learning. The very high engagement rating (92%) and strong preference over lectures (88%) demonstrate that students were not only learning but also enjoying the experience. This level of enthusiasm matters because students are generally more willing to explore challenging topics when they feel interested and emotionally connected to the material (Reyes et al., 2012; Zhoc et al., 2020). VR seems to provide this connection by creating an environment that feels interactive, dynamic, and different from their usual classroom routine.

The qualitative comments add depth to these findings. Students often mentioned that VR allowed them to "see what is happening inside the rock" or "finally understand how pores link together." These reflections suggest that the VR environment supported the development of mental models that students struggled to form from static images (Chen et al., 2024; Ha, 2020). By viewing deformation, rotation, and fluid movement in real time, students could make sense of relationships that might otherwise remain abstract. The sense of immersion also appeared to create a more memorable learning moment, something students felt they could recall and apply more easily (Kubr et al., 2024; Uriarte-Portillo et al., 2022).

Another notable outcome was the increase in student confidence. Many students reported feeling more assured about their ability to interpret deformation patterns and subsurface processes after using the VR module. This confidence is particularly important for final-year petroleum geoscience students, as they are preparing for professional roles that require strong spatial interpretation skills (Klippel et al., 2019). A boost in confidence may encourage them to approach future geoscience challenges with greater independence and curiosity (Willis et al., 2021).

A key strength of the VR module used in this study was its grounding in Malaysian reservoir characteristics. Students often find it easier to relate to local geological examples, and this familiarity may have contributed to the strong positive response (Harrison et al., 2024). While many VR tools are based on generic or international datasets, this study demonstrates the value of designing educational VR content that reflects local geology and industry contexts.

However, it is important to consider that VR-based learning does not always produce uniformly positive results. Some studies have reported limited or mixed outcomes, where VR primarily increased engagement without significantly improving conceptual understanding, or where results depended heavily on students' prior knowledge, task complexity, or the quality of VR implementation (Fang et al., 2025). These findings highlight that VR is not a universal solution and its effectiveness can vary; careful instructional design, alignment with learning objectives, and proper scaffolding are key factors in realizing meaningful learning gains.

Taken together, the findings show that VR is a highly effective complement to traditional teaching, especially in subjects that demand spatial reasoning and visualisation. It does not replace existing teaching methods, but it enriches them by offering a different way for students to interact with complex geoscience concepts (Liben et al., 2011). The combination of conceptual improvement, motivation, and positive student attitudes suggests that immersive technologies can play a meaningful role in improving geoscience education and preparing students for real-world application in the energy sector.

Conclusion

This study set out to examine how an immersive VR module could support students in understanding key geomechanics concepts and to explore their overall learning experience. The results clearly show that VR has meaningful value in the geoscience classroom. Students not only demonstrated better conceptual understanding after engaging with the module, but they also responded very positively to the immersive format. Many of the ideas that students traditionally struggle with such as deformation patterns, pore connectivity, and fluid movement became easier to interpret once they could see these processes unfold in three dimensions.

The consistently high enjoyment and engagement ratings suggest that VR does more than deliver content; it creates a learning environment that stimulates curiosity and encourages deeper exploration. The strong preference over conventional lectures highlights the growing need for teaching approaches that combine visual, interactive, and hands-on elements. For final-year petroleum geoscience students who will eventually work with real reservoir data, the ability to visualise subsurface behaviour is an important skill, and VR appears to support the development of this capability.

Another key outcome of this study is the rise in student confidence. Many participants felt more capable of explaining Geomechanical concepts after the VR session, indicating that immersive learning environments may help reduce uncertainty and support stronger self-efficacy in technical subjects. The use of Malaysian reservoir-based scenarios further strengthened the relevance of the experience, showing the benefits of designing VR content that matches local geological contexts.

Overall, the findings highlight the potential of VR to serve as an effective complementary tool in geoscience education. While it does not replace lectures or laboratory work, VR adds an essential dimension of visual clarity and experiential learning that traditional methods cannot offer. By making complex processes more intuitive and engaging, VR can help prepare students for industry demands and enrich the academic experience. The encouraging results from this study support the continued integration of immersive technologies into higher-education geoscience programmes.

Limitations and Future Studies

Although the findings of this study are promising, several limitations should be acknowledged to provide proper context for the results. First, the study involved a single cohort of 40 students from one academic programme. While this group represents typical final-year petroleum geoscience students at UTP, the sample size limits the generalisability of the results. Additional studies involving larger and more diverse groups of learners would help strengthen confidence in the broader applicability of the VR module.

Second, the study focused on short-term learning gains measured immediately after the VR session. Although students showed clear improvements in conceptual understanding, the research did not examine whether these gains were retained over time or transferred to other learning tasks, such as solving more complex geomechanical problems or interpreting real field data. Longitudinal studies or follow-up assessments would be valuable for determining the lasting impact of VR on students' learning.

Third, while students responded positively to the immersive experience, the study did not evaluate how different design features within the VR module contributed to learning outcomes. Factors such as movement control, visual detail, simulation speed, and interface usability may influence how effectively students learn. Future research could explore how specific elements of VR design support or hinder conceptual understanding.

Another limitation relates to the practical constraints of implementing VR in classroom settings. Hardware availability, setup time, and the need for technical support may affect the scalability of VR across larger classes or different institutions. Investigating efficient deployment strategies, multi-user options, or browser-based VR alternatives could help make the technology more accessible.

Looking forward, several avenues for future research and development emerge from this study. Expanding the VR module to include additional geoscience topics such as fracture mechanics, reservoir compaction, or CO_2 storage could provide a more comprehensive learning tool for students. There is also potential for incorporating interactive quizzes, adaptive tasks, or real-time feedback directly within the VR environment to support self-paced learning. Furthermore, exploring collaborative VR experiences, where multiple students interact in the same virtual space, may offer new opportunities for peer learning and group-based problem-solving.

Overall, while this study demonstrates the strong potential of VR for improving geoscience education, continued research and development are essential to refine the technology, expand its capabilities, and better understand its long-term educational impact.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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