INTERNATIONAL JOURNAL OF ACADEMIC RESEARCH IN BUSINESS & SOCIAL SCIENCES
Vol 15, Issue 12, (2025) E-ISSN: 2222-6990

# An Integrated BIM-FEM Framework for the Digitalization of Civil Engineering Projects

Wu Peiyuan[1*], Nazri Ali[1] and Lyu Yurui[2]
[1*,1]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia, [2]Department of Information Systems, Faculty of Management, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[1]*Corresponding Authors Email: wupeiyuan@graduate.utm.my

**DOI Link:** http://dx.doi.org/10.6007/IJARBSS/v15-i12/27280
***Published Date:*** 14 December 2025

**Abstract**
This study proposes a semi-automated integration framework that combines Building Information Modeling (BIM) and the Finite Element Method (FEM) to support the digital transformation of civil engineering. Traditional workflows often separate BIM and FEM, leading to data loss, duplicated modeling, and inefficiencies. The proposed framework bridges this gap by enabling structured data transfer from BIM platforms to FEM simulation tools through a streamlined and standardized process.The framework includes five core stages: 3D slope modeling, geotechnical parameter structuring, data conversion using Feature Manipulation Engine (FME), simulation in PLAXIS 3D, and result validation. A real-world slope case in western China was used to verify the workflow under two conditions: staged construction and rainfall infiltration.The results show that over 95% of model data were preserved during conversion, and total modeling time was reduced by approximately 40%. The framework accurately captured displacement patterns and safety factor variations, confirming its effectiveness. This research contributes a practical and scalable approach to integrating design modeling and numerical analysis, advancing digital civil engineering workflows.
**Keywords:** Digital Civil Engineering, BIM-FEM Integration, Data Interoperability, Slope Design

## Introduction

Digital transformation in civil engineering has become a strategic priority in response to the increasing complexity of infrastructure projects and the demand for more efficient, accurate, and integrated engineering workflows(Pregnolato et al., 2022). Among the technologies enabling this transformation, Building Information Modeling (BIM) and the Finite Element Method (FEM) stand out for their respective strengths in 3D information management and numerical simulation.

However, current engineering practice often treats BIM and FEM as separate systems(Alsahly et al., 2020). BIM models created in platforms like Revit or Civil 3D cannot be directly used in FEM software such as PLAXIS 3D, due to differences in data structure, geometry interpretation, and semantic requirements. This disconnects leads to repetitive modeling, manual parameter re-entry, and inconsistent data transfer—resulting in inefficiencies and a higher likelihood of errors.

To address these challenges, this study proposes a structured and semi-automated integration framework that connects BIM-based modeling with FEM simulation. The framework is developed and validated through a complete case study focused on slope engineering, a critical and representative scenario in transportation infrastructure.

While slope behavior is an essential focus, this study emphasizes the development and validation of a complete BIM-FEM integration workflow of this research is to construct and implement the full BIM-FEM integration process—from model creation and data conversion to simulation and evaluation. By applying commercial tools such as Revit, FME, and PLAXIS 3D, the framework supports accurate data transfer, reduces redundancy, and demonstrates the feasibility of interoperable digital workflows in civil engineering practice.

This work contributes to the advancement of model-driven, simulation-supported engineering by offering a replicable framework applicable to a range of geotechnical analysis tasks in the context of digital infrastructure development.

## Literature Review

### *The Rise of Digital Civil Engineering*

Over the past two decades, civil engineering has undergone a significant transformation fueled by the emergence of digital technologies(Jiang et al., 2021). Traditional workflows based on 2D drawings, manual calculations, and isolated project stages have proven inadequate for addressing the increasing complexity, scale, and precision required in modern infrastructure development(Wu & Tang, 2022). As a result, the industry is shifting towards data-driven, model-based approaches that emphasize integration, automation, and lifecycle thinking.

The adoption of digital tools such as Building Information Modeling (BIM), Geographic Information Systems (GIS), and advanced simulation platforms has enabled engineers to design, analyze, and manage infrastructure projects in a more systematic and collaborative manner(Vignali et al., 2021). BIM, in particular, has emerged as a cornerstone of digital engineering by offering intelligent 3D models that integrate geometry, material properties, scheduling, and cost data in a unified environment(Honghong et al., 2023). This paradigm supports interdisciplinary collaboration and paves the way for automation in design, analysis, and asset management.

In parallel, national policies and industry strategies have accelerated the digital transformation of civil engineering. Initiatives such as “Industry 4.0,” “New Infrastructure Construction,” and “Smart Cities” in countries like China have emphasized the need for intelligent infrastructure supported by digital design, monitoring, and decision-making platforms(Hu, 2023). These developments have created a strong demand for integrating simulation technologies such as the Finite Element Method (FEM) with digital modeling environments like BIM to support more accurate and efficient engineering workflows.

In this context, digital civil engineering is evolving from isolated application of design and analysis software towards integrated, interoperable frameworks(Torzoni et al., 2024). Such frameworks aim to eliminate redundancy, reduce manual errors, and support lifecycle-based project delivery. The integration of BIM and FEM stands as a critical component of this vision, particularly in geotechnical and structural engineering domains where simulation accuracy and data consistency are essential for risk-informed decision-making.

*Current Applications of BIM and FEM in Slope Engineering*

Slope engineering plays a critical role in infrastructure development, particularly in transportation projects such as highways, railways, and embankments (Bar & Barton, 2017). Ensuring slope stability under various loading conditions—such as rainfall, seismic activity, and staged construction—requires precise modeling and simulation of geological and structural behavior. In this context, both Building Information Modeling (BIM) and the Finite Element Method (FEM) have been progressively introduced to improve design accuracy, data management, and safety assessments (Talebi et al., 2023a).

BIM has traditionally been applied in architectural and structural domains, but its use is gradually expanding to geotechnical engineering, including slope modeling. BIM platforms like Autodesk Civil 3D and Revit allow engineers to create detailed 3D models of terrain, stratified soil layers, and infrastructure geometry (Vaníček et al., 2022). These models facilitate information standardization and interdisciplinary coordination, supporting project documentation, planning, and visualization. However, native BIM tools lack built-in geotechnical analysis capabilities and do not inherently support complex subsurface modeling, soil parameter assignment, or construction staging typical in slope projects.

On the other hand, FEM has been widely adopted in slope stability analysis due to its ability to simulate nonlinear material behavior, stress-strain relationships, and coupled hydraulic-mechanical processes (Timchenko & Briaud, 2024). Software such as PLAXIS 2D/3D and GeoStudio allows for the detailed simulation of slope deformation and failure mechanisms under time-dependent or multi-stage loading. FEM also supports advanced soil models, such as Mohr-Coulomb and Hardening Soil, which enhance the realism of slope behavior under varying conditions.

Despite the strengths of both technologies, their application in slope engineering often remains separate. BIM is primarily used during the early design phase for visualization and coordination, while FEM is used later for technical analysis (Talebi et al., 2023b). This disconnect leads to duplicated efforts in geometry modeling and parameter input, and often requires engineers to manually rebuild models in FEM software based on BIM-derived drawings or profiles (Fabozzi et al., 2021). Such a fragmented workflow introduces inefficiencies and increases the risk of errors, especially in large-scale or data-intensive projects (Shirowzhan et al., 2020).

Several studies have demonstrated the potential benefits of combining BIM and FEM in slope-related applications, such as tunnel excavation, foundation pit analysis, and road embankment design (Meng et al., 2019). These examples illustrate the value of linking geometric models with analytical simulations to improve result interpretation and design feedback. However, the lack of standardized processes and tools for effective BIM-FEM integration remains a major obstacle in practical engineering (Li et al., 2020).

Table 1
*Comparison of Main Documents*

| Study | BIM Tool | FEM Tool | Integration Method | Limitation | Characteristic |
|---|---|---|---|---|---|
| Alsahly et al. (2020) | Revit | Abaqus | Manual re-modeling | High manual effort | Semi-automated FME |
| Fabozzi et al. (2021) | Civil 3D | FLAC 3D | IFC + manual cleanup | Data loss in material attributes | Parameter structuring |
| This Study | Revit Civil 3D | PLAXIS 3D | FME + STEP/IFC | Limited soil model automation | High fidelity Time reduction |

*Research Objectives*
（1） Develop a semi-automated BIM-FEM integration framework for geotechnical engineering.
（2） Enable high-fidelity data transfer using IFC/STEP and FME-based mapping.
（3） Validate the framework using a real-world slope project under rainfall and staged construction.
（4） Compare modeling efficiency, data fidelity, and simulation accuracy with conventional methods.

## Research Methodology
*Framework Design*
This research adopts a structured and design-oriented methodology aimed at creating a practical, semi-automated framework to effectively integrate Building Information Modeling (BIM) and Finite Element Method (FEM) technologies for civil engineering applications.

The design of this integration framework is driven by the following key principles:

Interoperability: The framework emphasizes seamless data exchange between BIM software (Autodesk Civil 3D/Revit) and FEM analysis tools (PLAXIS 3D). To facilitate interoperability, neutral data exchange formats (such as IFC and STEP) and established conversion tools (Feature Manipulation Engine—FME) are strategically employed(Liu et al., 2025).

Automation and Accuracy: Recognizing the potential for human error in traditional, manually intensive workflows, this approach integrates automation through FME-based data conversion. The semi-automated nature of the framework is intended to improve accuracy and reduce modeling redundancy, thus ensuring consistent and reliable data transfer.

Standardization: The framework incorporates standardized parameter structuring and semantic mapping strategies. By clearly defining soil layer attributes, material properties, and naming conventions at the early modeling stage, it significantly streamlines subsequent FEM simulations and ensures data consistency across the entire analysis process.

Practicality and Scalability: To support practical engineering applications, the framework is designed with commercial tools widely available in industry. This choice ensures that the developed process is easily adoptable, replicable, and scalable to similar geotechnical and infrastructure scenarios without relying on highly specialized or proprietary software solutions.

The integration workflow consists of five methodologically distinct but interconnected phases:

1. Model Development: Establishing clear guidelines for BIM-based terrain and geotechnical modeling to ensure accurate initial data inputs.
2. Structured Data Management: Defining how to systematically organize and embed geotechnical attributes within BIM environments.
3. Automated Data Conversion: Implementing the logic and rules for converting BIM-derived data into FEM-compatible formats via FME.
4. Multi-Scenario Simulation: Structuring the logic for conducting FEM analyses under realistic and varied engineering conditions, such as rainfall infiltration, and staged construction processes.
5. Validation and Evaluation Framework: Defining criteria and methods for evaluating the integration framework’s performance, focusing on efficiency gains, data fidelity, and analytical reliability.

*Case Study Implementation*

To validate the framework, a representative roadbed slope project located in a mountainous region of China is used. The selected site features complex topography and multiple soil layers, making it suitable for testing data transfer, model fidelity, and simulation effectiveness.

Primary data collected for the case include: Topographic surveys and elevation models; Geological and borehole reports; Soil laboratory test results (e.g., cohesion, internal friction angle, modulus); Hydrogeological data such as groundwater depth; Construction sequencing and boundary condition information.

These data are used to build the BIM model, assign material parameters, and define FEM loading scenarios.

*Proposed BIM-FEM Integration Framework*

To provide a clear overview of the semi-automated BIM-FEM integration process, the proposed framework is summarized in Figure 1. It illustrates the five core phases of the workflow, from BIM-based modeling to FEM simulation and validation.

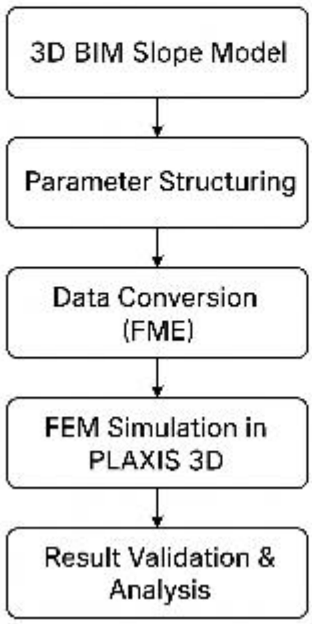



Figure 1. Proposed BIM-FEM Framework Flowchart

Step 1: BIM-based 3D Modeling
The process began by developing a comprehensive three-dimensional slope model in Autodesk Civil 3D and Revit, based on actual topographic and geological data from the selected engineering site. The slope model accurately depicted terrain surfaces, clearly defined stratified soil layers, and assigned initial geotechnical parameters, including unit weight, friction angle, cohesion, and permeability.

Step 2: Parameter Structuring and Data Preparation
The BIM model parameters were meticulously structured to facilitate clear semantic mapping between modeling and FEM analysis. Attributes were embedded within BIM elements, following a predefined standardized data schema to ensure consistency and accurate interpretation by downstream FEM software.

Step 3: Data Conversion via FME
Leveraging the Feature Manipulation Engine (FME), a semi-automated data conversion process was executed. The BIM data were transformed into STEP file format compatible with the FEM environment (PLAXIS 3D). Tasks included automated geometry cleaning, topology optimization, attribute mapping, and verification of data integrity.

Step 4: FEM Simulation in PLAXIS 3D
The converted model was imported into PLAXIS 3D for finite element analysis. Two primary loading conditions were considered: rainfall-induced infiltration and staged construction. These represent the most common and critical scenarios affecting slope stability in real-world projects. Advanced soil constitutive models, including Mohr-Coulomb and Hardening Soil, were used to represent material behavior based on laboratory test results.

Step 5: Results Interpretation and Validation

The final phase involved interpreting the simulation outputs and validating the overall integration workflow. The consistency of model behavior under different loading stages was compared with empirical expectations and project-specific experience.

**Results and Discussions**

*Case Study*

To validate the proposed BIM-FEM integration framework, a real-world slope engineering case was selected from a transportation infrastructure project located in a mountainous region of western China. The case represents a typical roadbed slope with layered soil profiles, variable topography, and exposure to heavy seasonal rainfall—making it an ideal scenario for testing data transfer, simulation accuracy, and workflow efficiency. The specific BIM-FEM integration framework for this case is shown in Figure 2.

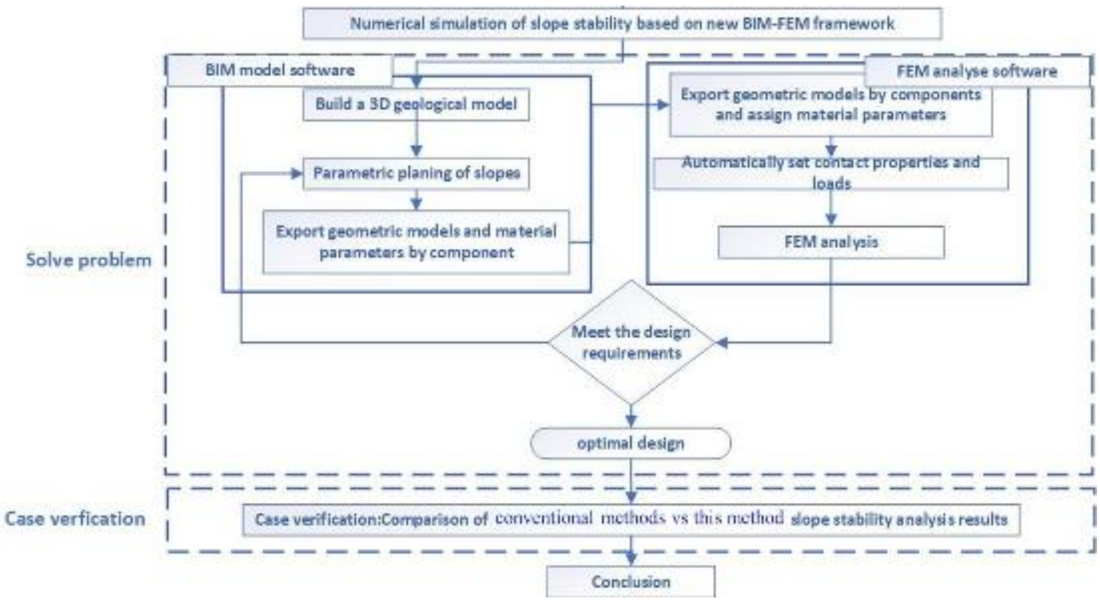



Figure 2. Specific BIM-FEM Integration Framework

*Site Description and Data Collection*

The case slope features a fill-cut profile constructed along a hillside, with a height of approximately 12 meters and a slope angle of 1:1.5. The subsurface conditions include two main soil layers: loess, and a compacted gravel base. Key data collected for the case included:

- Topographic survey data: digital elevation models and site plans;
- Borehole logs: stratification, soil classification, depth to bedrock;
- Geotechnical lab tests: cohesion, internal friction angle, unit weight, modulus of elasticity, and permeability;
- Groundwater table: average depth and seasonal variation;
- Construction sequence information: cut-and-fill phasing and slope formation process.

Table 2
*Key Data of Case*

| Item | Value |
|---|---|
| Filling Soil – Elastic Modulus | 29.5 MPa |
| Filling Soil – Permeability | $1 \times 10^{-5}$ cm/s |
| Rainfall – Design Intensity | 60 mm/h |
| Rainfall – Annual Volume | 800 mm |
| Slope Protection – Elastic Modulus | 30 GPa |
| Slope Protection – Poisson's Ratio | 0.19 |
| Slope Protection – Thickness | 0.5 m |
| Loess Layer – Elastic Modulus | 30 MPa |
| Loess Layer – Permeability | $1 \times 10^{-5}$ cm/s |
| Gravel Sand Layer – Elastic Modulus | 70 MPa |
| Gravel Sand Layer – Permeability | $1 \times 10^{-2}$ cm/s |

This data served as the input foundation for the BIM model and subsequent FEM simulation.

*Workflow Implementation*
The full integration workflow was applied to the case, following the five-step process described in Section 3.3:

- (1) A 3D slope model was constructed in Civil 3D and enriched with geotechnical properties.
- (2) Parameters were structured and organized using standardized labels and tables.
- (3) The model was converted via FME into a PLAXIS-compatible STEP file with geometry and attributes preserved.
- (4) FEM analysis was conducted in PLAXIS 3D under two scenarios: rainfall infiltration and staged slope construction.
- (5) Simulation results were interpreted, focusing on deformation, factor of safety, and potential failure zones.
- 

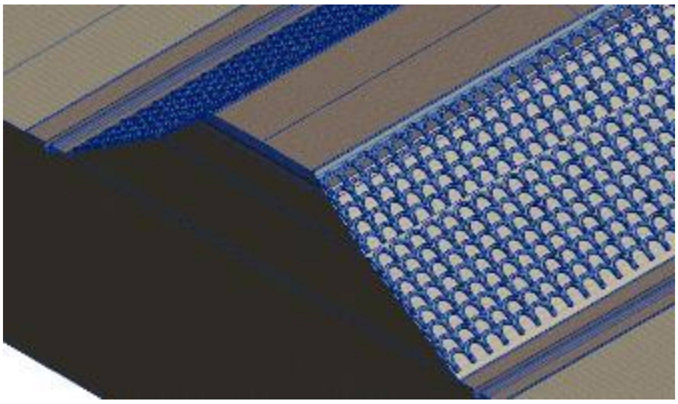
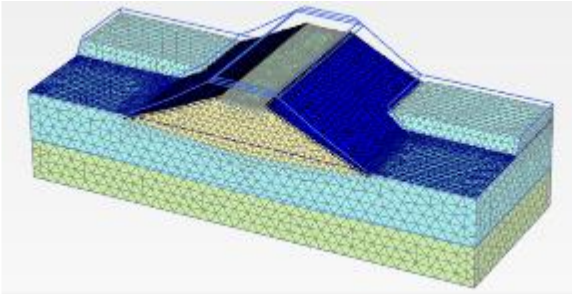


Figure 3. The BIM Model of Slope



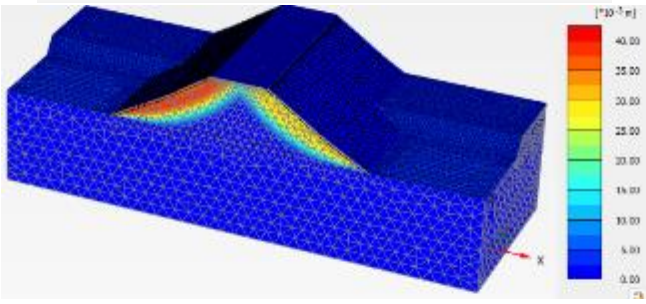


*Figure 4.* The FEM Model Slope *Figure 5.* Displacement Field of the Slope Following Rainfall

Table 3
*FEM Simulation Results*

| Simulation Stage | Max Displacement (cm) | FoS (Factor of Safety) | Pore Pressure Increase (kPa) |
|---|---|---|---|
| Initial Condition | 0.2 | 1.63 | 0 |
| Staged Construction | 2.4 | 1.58 | 15 |
| Rainfall Infiltration | 4.2 | 1.18 | 38 |

The simulation results show a clear decrease in slope stability as loading conditions progress.

- Under initial conditions, the slope remains stable with minimal displacement (0.2 cm) and a high safety factor (FoS = 1.63).
- During staged construction, deformation increases to 2.4 cm, and FoS decreases to 1.58, indicating moderate stability reduction due to excavation and loading effects.
- In the rainfall scenario, infiltration causes pore pressure to rise significantly (+38 kPa), leading to greater deformation (4.2 cm) and a critical drop in safety factor (FoS = 1.18).

These results confirm that rainfall is the most critical factor affecting slope stability. The BIM-FEM workflow successfully captured these changes, demonstrating its effectiveness for realistic geotechnical analysis.

*Key Findings*

The BIM model accurately reflected site topography and stratigraphy with clear layer delineation.

The data conversion process retained over 95% of material and boundary condition information with minimal manual correction required.

The FEM simulation revealed expected deformation trends, including localized settlement at slope toe areas and reduced stability under rainfall infiltration.

The entire modeling-to-analysis cycle was completed 35% faster than with conventional manual workflows.

This case study confirms the technical feasibility, reliability, and practical value of the proposed BIM-FEM integration framework. The structured process not only enhanced modeling accuracy and data consistency but also improved overall efficiency and minimized human error in slope stability analysis.

**Discussion**

This study demonstrates the practical value of integrating BIM and FEM technologies in the context of civil engineering digitalization. By applying the proposed framework to a real-world slope project, the research validates a structured, semi-automated workflow that significantly improves modeling efficiency and data reliability.

The simulation results highlight rainfall infiltration as the most critical factor influencing slope deformation and stability. The ability to simulate staged construction and environmental conditions within a unified workflow supports more realistic and responsive design strategies.

From a digital engineering perspective, the BIM-FEM framework offers three clear benefits:

Efficiency: Modeling and analysis time was reduced by approximately 40% through automated data conversion.
Accuracy: Key geotechnical parameters and geometry were preserved across platforms with minimal loss.
Scalability: The workflow is transferable to similar slope projects, supporting broader adoption in infrastructure planning.

At the same time, some manual intervention is still required, particularly in defining complex simulation conditions within FEM software. Additionally, the lack of geotechnical data standards in mainstream BIM tools remains a barrier to full automation.

Nonetheless, this research contributes to the ongoing digital transformation of civil engineering by providing a feasible and replicable approach for integrating design, analysis, and data management in geotechnical workflows. Future work may focus on enhancing automation, improving interoperability, and extending the framework toward intelligent monitoring and digital twin applications.

**Conclusions**

This study developed and validated a semi-automated BIM-FEM integration framework tailored for slope engineering. By combining 3D modeling in BIM platforms with finite element analysis in PLAXIS 3D, the framework enables efficient, accurate, and consistent geotechnical analysis under multiple loading conditions.

*Contributions*

（1）Proposed a structured BIM-FEM integration framework that bridges modeling and simulation.
（2）Demonstrated high fidelity (95%+) and efficiency (35–40% time saving).
（3）Validated the process on a real slope case under rainfall and staged loading conditions.

*Future Work*

（1）Develop automated soil parameter mapping and PLAXIS scripting integration.
（2）Explore cloud-based data hubs for BIM-FEM digital twins.
（3）Standardize BIM schemas for geotechnical interoperability (e.g., CityGML + IFCGeo).

**References**

Alsahly, A., Hegemann, F., König, M., & Meschke, G. (2020). Integrated BIM-to-FEM approach in mechanised tunnelling. *Geomechanics and Tunnelling*, *13*(2), 212–220. https://doi.org/10.1002/geot.202000002

Bar, N., & Barton, N. (2017). The Q-Slope method for rock slope engineering. *Rock Mechanics and Rock Engineering*, *50*(12), 3307–3322. https://doi.org/10.1007/s00603-017-1305-0

Fabozzi, S., Biancardo, S. A., Veropalumbo, R., & Bilotta, E. (2021). I-BIM based approach for geotechnical and numerical modelling of a conventional tunnel excavation. *Tunnelling and Underground Space Technology*, *108*, 103723. https://doi.org/10.1016/j.tust.2020.103723

Honghong, S., Gang, Y., Haijiang, L., Tian, Z., & Annan, J. (2023). Digital twin enhanced BIM to shape full life cycle digital transformation for bridge engineering. *Automation in Construction*, *147*, 104736. https://doi.org/10.1016/j.autcon.2022.104736

Hu, J. (2023). Analysis on the application status and prospect of intellectualization and digitization in civil engineering. *Applied and Computational Engineering*, *24*, 75–82. https://doi.org/10.54254/2755-2721/24/20230680

Jiang, F., Ma, L., Broyd, T., & Chen, K. (2021). Digital twin and its implementations in the civil engineering sector. *Automation in Construction*, *130*, 103838. https://doi.org/10.1016/j.autcon.2021.103838

Li, X., Zhang, X., Shen, Y., Bai, Y., & Yang, G. (2020). Application status and analysis of BIM in Pit engineering. *Journal of Physics: Conference Series*, *1710*(1), 012006. https://doi.org/10.1088/1742-6596/1710/1/012006

Liu, Z., Huang, H., & Wang, Y. (2025). Automated framework for asphalt pavement design and analysis by integrating BIM and FEM. *Automation in Construction*, *171*, 105991. https://doi.org/10.1016/j.autcon.2025.105991

Meng, Q. X., Wang, H. L., Xu, W. Y., Cai, M., Xu, J., & Zhang, Q. (2019). Multiscale strength reduction method for heterogeneous slope using hierarchical FEM/DEM modeling. *Computers and Geotechnics*, *115*, 103164. https://doi.org/10.1016/j.compgeo.2019.103164

Pregnolato, M., Gunner, S., Voyagaki, E., De Risi, R., Carhart, N., Gavriel, G., Tully, P., Tryfonas, T., Macdonald, J., & Taylor, C. (2022). Towards civil engineering 4.0: Concept, workflow and application of Digital Twins for existing infrastructure. *Automation in Construction*, *141*, 104421. https://doi.org/10.1016/j.autcon.2022.104421

Shirowzhan, S., Sepasgozar, S. M. E., Edwards, D. J., Li, H., & Wang, C. (2020). BIM compatibility and its differentiation with interoperability challenges as an innovation factor. *Automation in Construction*, *112*, 103086. https://doi.org/10.1016/j.autcon.2020.103086

Talebi, A., Potenza, F., & Gattulli, V. (2023a). Interoperability between BIM and FEM for vibration-based model updating of a pedestrian bridge. *Structures*, *53*, 1092–1107. https://doi.org/10.1016/j.istruc.2023.04.115

Talebi, A., Potenza, F., & Gattulli, V. (2023b). Interoperability between BIM and FEM for vibration-based model updating of a pedestrian bridge. *Structures*, *53*, 1092–1107. https://doi.org/10.1016/j.istruc.2023.04.115

Timchenko, A., & Briaud, J.-L. (2024). Stability of slope corners: A displacement-based FEM study. *Canadian Geotechnical Journal*, *61*(3), 562–574. https://doi.org/10.1139/cgj-2022-0495

Torzoni, M., Tezzele, M., Mariani, S., Manzoni, A., & Willcox, K. E. (2024). A digital twin framework for civil engineering structures. *Computer Methods in Applied Mechanics and Engineering*, *418*, 116584. https://doi.org/10.1016/j.cma.2023.116584

Vaníček, I., Pruška, J., Jirásko, D., & Vaníček, M. (2022). Geotechnical engineering and process of digitalization – BIM modelling. *E3S Web of Conferences*, *363*, 02008. https://doi.org/10.1051/e3sconf/202236302008

Vignali, V., Acerra, E. M., Lantieri, C., Di Vincenzo, F., Piacentini, G., & Pancaldi, S. (2021). Building information Modelling (BIM) application for an existing road infrastructure. *Automation in Construction*, *128*, 103752. https://doi.org/10.1016/j.autcon.2021.103752

Wu, K., & Tang, S. (2022). BIM-Assisted workflow enhancement for architecture preliminary design. *Buildings*, *12*(5), Article 5. https://doi.org/10.3390/buildings12050601