

Spatial modelling for bridge construction environment towards geospatial digital twin

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ABSTRACT

Geospatial digital twin (GDT) presents an opportunity to map the physical geographic environment into the virtual geographic environment, offering a new perspective towards intelligent construction. However, the application of GDT in engineering construction is still in its infancy. There is a gap from the concept idea to system implementation and primary application, particularly in bridge construction. Following the connotation of GDT, this article proposes a spatial modelling approach for bridge environments aimed at supporting intelligent bridge construction. The logic model, numerical simulation, spatial modelling, and visual representation involved in bridge digital construction are discussed in detail. Finally, we developed a WebGL-based prototype system and selected a mega suspension bridge under construction as the case for experimental analysis. The experimental results demonstrate that the proposed approach can effectively support the generation of 3D scenes of the bridge environment and the visual simulation of the bridge construction. Specifically, numerical simulation of multi-field coupling and spatial modelling of the bridge environment are beneficial for pre-discovering hidden risks in construction, and the visual simulation of bridge construction could serve as a digital window to assist in upgrading intelligence in construction. The proposed method aligns with the concept of GDT and offers a tailored solution for modelling virtual geographic environments in the context of GDT.

1. Introduction

Bridges are critical nodes for the interconnection of transportation systems (Zhou and Zhang, 2019). In particular, high-speed rail (HSR) has emerged as a reliable and appealing alternative to transportation, and bridges have gradually become essential parts of HSR infrastructures for crossing natural and artificial obstacles (Kang et al., 2018; Rocha et al., 2014). It is clear that the fever for the HSR will continue to rise in the foreseeable future (He et al. 2017).

The extension of the HSR network will face more unknown and complex environment, which present numerous engineering challenges for bridge construction. There are many uncertainties in mechanical behavior and construction process under environmental factors. The most typical case is that the canyon wind and significant temperature differences in the mountain areas will affect the bridge structure. Therefore, the integrated utilization of cutting-edge technologies to improve the digitalization of bridge construction is one of the most promising solutions to the above engineering challenges (Glema, 2017;

Li et al., 2022).

Bridge construction digitalization refers to the comprehensive management of the bridge construction process, thereby improving the efficiency and quality of bridge construction (Zhao et al., 2020; Boton, 2018). Building Information Modeling (BIM), a digital representation of the physical and functional characteristics of the entity (Xu et al., 2014), has created a new paradigm shift in the discipline of construction engineering and also drives the transition from paper-based to 2D drawings-based and to the digital model-based of bridge construction (Wang et al., 2014; Liu et al., 2014; Costin et al., 2018; Wang et al., 2022; Dashti et al., 2021). Nevertheless, BIM primarily emphasizes component-level refinement modeling but neglects the crucial role of geospatial information, including terrain and environmental data, in bridge construction (Ning et al., 2020).

Subsequently, some researchers have grown tremendous interest in applying BIM and Geographic Information Science (GIS) to construction engineering, as the two technologies complement each other (Sun et al., 2019; Wei et al., 2021). Integrating BIM and GIS promotes a giant leap

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forward from micro-level to macro-level applications of BIM, enabling designers to ground their BIM work within a real-world context and offering numerous benefits in terms of scale and scope. To the author's knowledge, the integration of BIM and GIS primarily concerns the static modelling of bridge objects and representation, with limited consideration for the spatial modelling of environmental factors and mechanical behavior simulation results in bridge construction.

Additionally, with the rapid advancement of WebGIS technologies, particularly WebGL, there has been an increasing trend toward visualizing BIM models and mechanical simulation results directly within web browsers. Such web-based environments provide user-friendly interfaces for validating Finite Element Analysis (FEA) simulation outputs and enabling their dissemination to a wide range of stakeholders (Kang et al., 2021; Xu et al., 2026). However, most mechanical simulation software restricts access to simulation results to specialized professional tools, limiting their integration into digital management systems (Xu et al., 2026). To facilitate seamless integration between digital simulation and geovisualization, researchers have explored using open-source analysis platforms, such as OpenSees and FreeFEM, to simulate mechanical behavior. For instance, Mazzei and Quaroni (2021) proposed integrating OpenSees data models into 3D WebGIS to support bridge monitoring and visualization. Nevertheless, to the best of the authors' knowledge, existing methods primarily focus on structure-centered mechanical simulation, with limited attention to the coupled effects of multiple environmental factors on mechanical behavior during bridge construction.

In this context, there is a growing need for a more comprehensive paradigm capable of establishing the connection between physical construction processes and their corresponding virtual representations. Digital Twin (DT), proposed by Michael Grieves in 2003, has been recognized as a critical enabler for transforming to Industry 4.0 (Grieves and Vickers, 2017; Broo et al., 2022; Pregnolato et al., 2022; Broo and Schooling, 2021). In general, DT refers to a mirror and digital depiction of the physical entity, which can dynamically imitate the physical entity's properties, state, and behavior in the virtual space, thus providing a new perspective for people to know and understand the real world (Qi et al., 2021). In a "trial before construction" manner, DT-enabled virtual construction can dynamically simulate the construction activities of physical entities in the virtual environment, which can be used to pre-discover the problems that arise in actual construction (Kim et al., 2013; Jiang et al., 2021). However, in the field of bridge construction, traditional DT frameworks mainly focus on the construction schedule projection or the bridge structure itself, ignoring the influence of the surrounding geographical environment on the construction process, as noted earlier.

Geospatial digital twin (GDT) is an expansion and development of DT in the direction of the geography discipline (Döllner, 2020; Lin et al., 2022; Zhang et al., 2024). In comparison to DT, it focuses more on the virtualisation of the physical world in the geospatial dimension, possesses a unified geographical spatiotemporal reference, and emphasises the interactions and influences between elements within the environmental system (Lü et al., 2023; Ellul et al., 2024). More importantly, GDT can represent, analyse and process geographic data at different spatial scales and closely integrate with the real geographic environment to dynamically reflect the behavioural changes of geographic objects (Lin et al., 2022; Zhu et al., 2024b). These features make GDT more suitable than DT for simulating large-scale spatial objects and geographic areas, especially bridge construction environments (Liang et al., 2024; Li et al., 2024).

At present, the GDT concept is still in its infancy, with a noticeable gap between conceptualization and practical system implementation, especially in bridge construction. In this context, following the connotation of GDT and intelligent construction, we propose a GDT-oriented spatial modelling approach for bridge construction environment. The original contribution of this article is the design and implementation of a GDT-oriented modelling framework for bridge environment considering

logic model design, numerical simulation of multi-field coupling, spatial modelling of simulation results, and visual representation involved in bridge construction. Applying GDT to bridge construction has the following potential benefits: (1) The complicated geological conditions and unpredictable physical environment bring significant uncertainty to bridge construction safety. However, GDT-oriented numerical simulation and high-fidelity spatial modelling can support the comprehensive perception of the natural environment of bridge construction and reduce hidden risks. (2) Bridge construction is dynamic, complex, and lengthy. The GDT-oriented 3D/4D visual representation can support comparing the as-planned and construction process views, promote stakeholder communication, and optimize the construction plan. Our aim is to support the comprehensive perception of the bridge environment and pre-deduction of the invisible environmental risks, thus improving bridge construction quality.

The remainder of this paper is structured as follows. Section 2.1 outlines an overall framework of the proposed approach. Sections 2.2, 2.3, 2.4 and 2.5 introduce the logical model design, numerical simulation of multi-field coupling, spatial modelling of bridge environments, and multi-dimensional visual simulation of bridge construction, respectively. Section 3 develops a prototype system and conducts experimental analysis. Sections 4 and 5 present the discussion and conclusion.

2. Methodology

2.1. A GDT-oriented modelling framework for bridge construction environments

The key to GDT is using the virtual geographic environment to explore and inform the physical geographic world (Batty, 2018; Wu et al., 2022; Qi and Tao, 2018; Ye et al., 2023; Zhang et al., 2025). Following the connotation of GDT, we design a spatial modelling framework for bridge construction environments to build a closed loop between the physical site and the virtual world, as shown in Fig. 1.

The left side of the figure illustrates the physical construction site of the bridge, where numerical simulation is performed to analyze environmental and structural conditions. The logic model defines the objects and relationships within the virtual bridge environment at a conceptual level, guiding the integration of simulation results and spatial modelling of bridge environments. The right side represents the virtual environment, which provides high-fidelity models of bridge components and the corresponding environmental factors. These results are then communicated back to the actual site through visual simulation, thus guiding the bridge construction process.

2.2. Logic model of the virtual environment for bridge construction

The virtual environment (VE) is an accurate, objective, and complete mapping of the physical entity (PE) in digital space (Tao et al., 2019). Following the DT information model proposed by Tao et al. (2019) and Tao et al. (2022) and considering the characteristics of the bridge construction, we design a logic model of the VE, which provides a reference guide for implementing the subsequent spatial modelling and virtual representation of bridge construction. As shown in Eq. (1):

$$VE = \langle L_v, G_v, P_v, B_v | R_t, R_s, R_m \rangle \quad (1)$$

VE indicates the virtual environment of bridge construction that contains virtual objects and relationships. L_v , G_v , P_v , and B_v represent landscape model, geometry model, physical model, and behavior model, respectively. R_t , R_s , and R_m denote time relationship, spatial relationship, and semantic relationship.

2.2.1. Description of virtual objects

Landscape model (L_v) depicts the geographic environment sur-

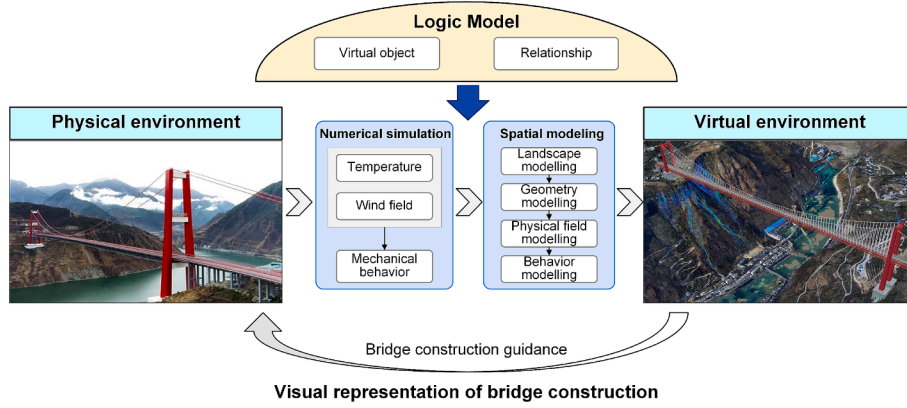


Fig. 1. A GDT-oriented modelling framework for bridge construction environments.

rounding the bridge construction, including natural resources (e.g., forests, arable lands, rivers) and artificial objects (e.g., buildings, roads), which serve as the representation foundation for the geometry model, physical model, and behavior model.

Geometry model (G_v) accurately describes the bridge's geometric features, including its type, size, and position. A high-fidelity virtual bridge scene can be generated based on the geometry models, spatio-temporally consistent with and visually closer to the bridge PE.

Physical model (P_v) integrates the physical properties into the geometry model (G_v), which derives from the natural environment of the bridge construction. In our case, we mainly consider the impact of canyon wind and temperature on the bridge.

Behavior model (B_v) capture each bridge component's mechanical behavior and changes in the construction process. In our case, we mainly consider the impact of stress change under wind-temperature effects.

2.2.2. Classification of relationships

Time relationship (R_t) refers to mapping the bridge construction cycle and schedule map to a timeline in digital space, including time points, intervals, and sequences. Time points indicate the specific node where the bridge component generation. Time interval describes the time span between two construction events. Time sequence defines the

chronological order of events in bridge construction. These time relationships are vital to the subsequent visual representation of bridge construction.

Spatial relationship (R_s) specifies the location of an entity in relation to another entity, which enables the correct layout expression of bridge components. In this article, we adopt the spatial constraint rules proposed by Li et al. (2023) to achieve the seamless integration of the bridge components, which include location, topology, and scale.

Semantic relationship (R_m) generally includes inheritance, association, aggregation, and composition, focusing on the logical relationship between entities (Ding et al., 2022). Inheritance refers to the inheritance relationship between a superclass and its corresponding subclasses. Association describes a general relationship between two entities without dependencies. Aggregation indicates that one object is part of another object to which it is attached. Composition is a stronger whole-part relationship than aggregation, where the part aligns with the life cycle of the whole.

2.3. Numerical simulation of physical field and mechanical behavior

2.3.1. Numerical simulation of temperature field

The numerical simulation calculation process for the temperature

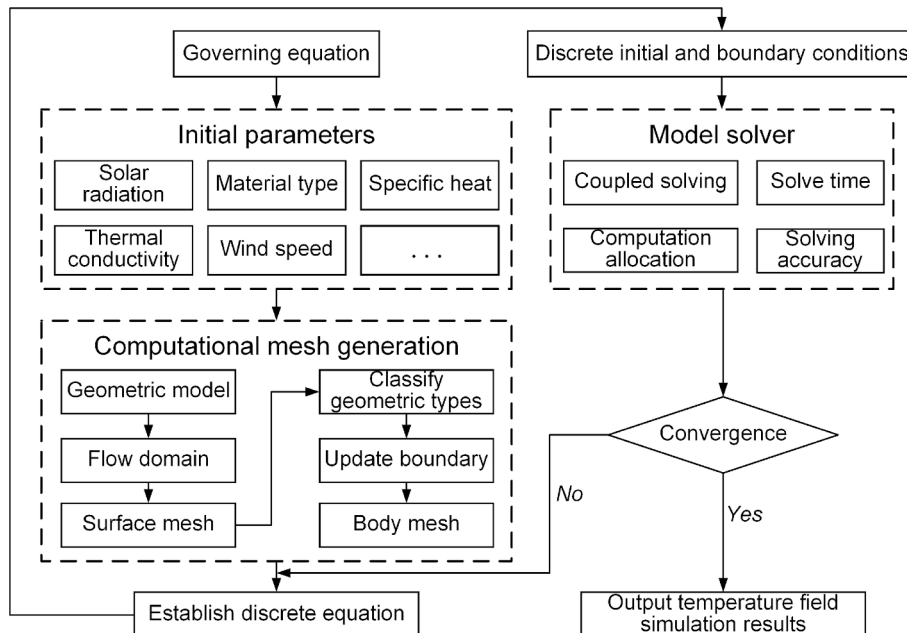


Fig. 2. Numerical simulation calculation process of temperature field of mountain bridges.

field of mountainous bridges is shown in Fig. 2.

First, drawing upon the fundamental principles of computational fluid dynamics, namely the conservation laws of mass, momentum, and energy, the governing equations for simulating the temperature field of mountainous bridges are formulated; Next, the initial parameters and boundary conditions for the simulation are specified, including thermodynamic coefficients, inlet and outlet flow velocities; Then, the geometric models of the bridge and surrounding terrain are discretized to generate a solid mesh model, which serves as the input data for the simulation calculations; Finally, the discrete equations are solved iteratively using numerical methods to obtain the simulated temperature field of mountainous bridges.

2.3.2. Wind field simulation in canyon bridge environment

The work flow for simulating wind field in canyon bridge environment is shown in Fig. 3. First, a geometric model of the wind field domain is constructed, encompassing the bridge and its surrounding terrain, while minimizing the influence of inlet and outlet boundary conditions on the simulation accuracy. Next, the model is discretized into computational mesh elements. The mesh density is refined in complex near-ground regions and appropriately coarsened in higher-altitude areas according to the spatial characteristics of the flow field. Subsequently, boundary conditions, including velocity inlets, pressure outlets, no-slip walls, and symmetry planes, are prescribed based on the actual wind field characteristics. The governing equations are then formulated in accordance with the conservation laws of mass, momentum, and energy. Finally, these equations are solved iteratively to obtain the numerical simulation results of the wind field around the mountainous canyon bridge.

2.3.3. Mechanical behavior simulation under wind-temperature coupling effects

The mechanical behavior reflects the stress distribution of the bridge in the working environment, which is an essential factor in ensuring safe

construction. The stress is influenced not only by the bridge's self-weight but also by environmental factors such as wind and temperature. Therefore, this section introduces the stress simulation under wind-temperature coupling effects, as illustrated in Fig. 4.

First, the external load conditions are specified, including wind, temperature, and dead weight, which constitute the primary external forces acting on the bridge structure; Next, initial parameters such as the geometric model and boundary conditions are established to characterize the physical attributes of the bridge; Subsequently, the finite element model is developed, wherein the structural geometry and boundary conditions are defined and applied. The model is then discretized into finite elements during the mesh generation stage, where the element type, grid size, and mesh connectivity are specified. Mesh refinement is applied in regions with complex geometries to enhance the accuracy of the numerical analysis. Once the model and mesh are established, the solution process begins, during which the governing equations are solved to obtain the stress distribution of the bridge.

2.4. Spatial modelling for bridge environments

Spatial modelling is the abstracting and simulating of real-world spatial data, which can help better understand the bridge environment and its impact on the bridge construction process. This section will introduce the spatial modelling approach for bridge environments from four parts: surrounding landscape, bridge geometry, physical field, and mechanical behavior, as previously mentioned.

2.4.1. Landscape modelling for the bridge construction

The virtual landscape serves as the foundation for presenting the various factors that influence bridge construction, enabling the stakeholder to better perceive the natural environment for bridge construction. Therefore, the initial step in spatial modelling of the bridge construction environment is to establish a landscape model. First, we use the Digital Elevation Model (DEM) to build a basic terrain model,

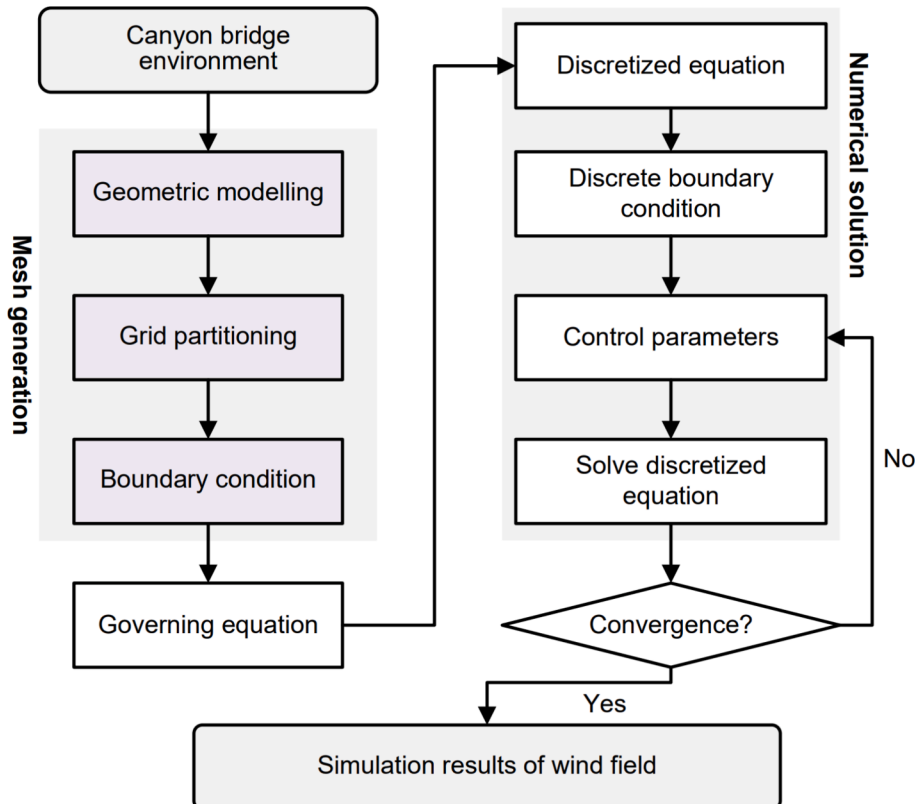


Fig. 3. The numerical simulation process for wind field around the mountainous canyon bridge.

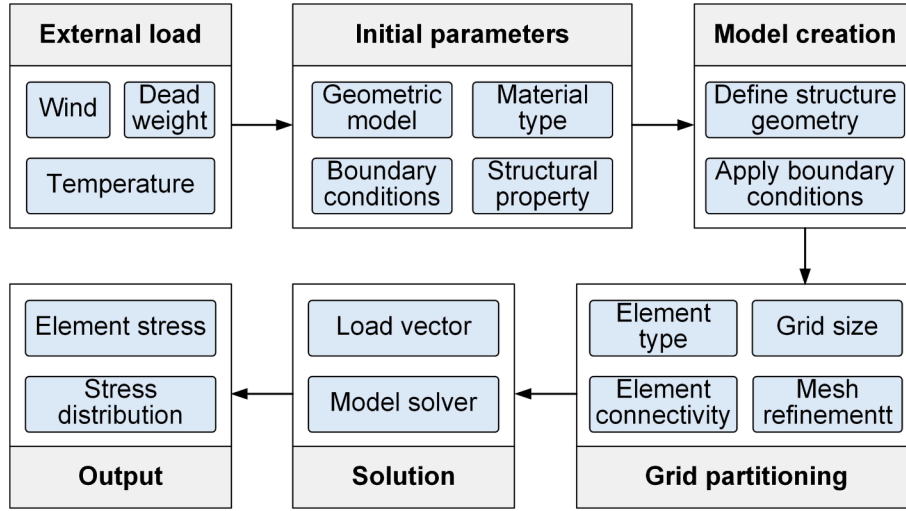


Fig. 4. Mechanical behavior simulation under wind-temperature coupling effects.

thereby ensuring the accurate restoration of the topographic relief of the surface. Second, we overlap the Digital Surface Model (DSM) data on top of this to add the height information of buildings, vegetation and other features around the bridge to the terrain model to ensure the comprehensiveness and authenticity of the environment. Finally, we employ satellite images as a texture source to enhance the surface details through texture mapping. This approach enables the generation of a highly realistic virtual landscape, which can be employed for the spatial modelling of the bridge environment.

2.4.2. Bridge geometry modelling

Bridge geometry modelling is the process of abstracting and digitizing a natural bridge, as shown in Fig. 6. The bridge is generally built using an assembly approach, where each component is equivalent to a virtual primitive model. The primitive component of bridge modelling includes the following aspects: 3D abstraction, data acquisition, geometric modelling, texture mapping, and model optimization, as shown in Fig. 5. Subsequently, these primitive models will be combined under the constraints and guidance of the time, spatial and semantic relationships to produce a bridge scene in 3D.

2.4.3. Physical field modelling

As previously noted, bridges are typically constructed in complex environments that present challenging topography and the effects of

physical fields (e.g., temperature, wind). Therefore, this article presents spatial modelling for the simulation results of two main physical factors to pre-perceive the hidden risks in advance.

1. Temperature field

The sparse temperature points in the simulation should couple with the environment temperature. In achieve this, we implement an adaptive inverse distance weighted (AIDW) algorithm to model the temperature field surrounding the bridge construction (Li et al., 2025).

IDW assumes that things close to one another are more alike than those farther apart, which aligns with the idea of Tobler's first law of geography. The closer the distance between the estimating and sampling points, the more significant the weight assigned. The concept describes in Equation (2):

$$t_j = \sum_{i=1}^n \lambda_i t_i \quad (2)$$

t_j represents the temperature value of the j^{th} point to be estimated, t_i indicates the value of the i^{th} sampling point, λ_i denotes the weight corresponding to the i^{th} sampling point, and n is the number of sampling points. λ can be further calculated using Eq. (3):

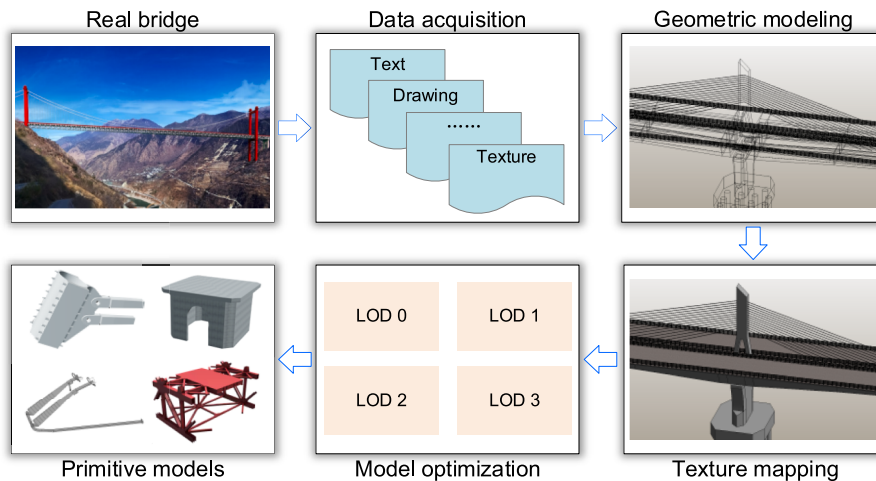


Fig. 5. The general process of geometry modelling of bridge primitive models.

$$\lambda_j = \frac{\left(\frac{1}{d_{ij}}\right)^\mu}{\sum_{i=1}^n \left(\frac{1}{d_{ij}}\right)^\mu} \quad (3)$$

d_{ij} denotes the distance between the i th sampling point (x_i, y_i, z_i) to the j th point to be estimated (x_j, y_j, z_j) . μ denotes the power of weights. In our case, the μ value adaptively varies depending on the material of the bridge components.

2. Wind field

In general, the simulation results of the wind include coordinates, velocity, pressure, and extent. In this section, the streamline will be used to model the wind field in geospatial space, intending to represent the spatiotemporal characteristics of the wind field. Fig. 6 shows the generative process of wind field modelling.

- (1) Spatialization. The rows and columns of the wind field are converted into a global coordinate system, and grids are used as the initial wind vector field. Each grid is assigned the velocity in the UV direction and the resultant velocity.
- (2) Interpolation. The initial wind vector field nodes are sparse and discrete, insufficient to present the wind trajectory. Therefore, the bilinear interpolation algorithm is adopted to interpolate the wind speed in U and V directions. In Fig. 4, for instance, there are four wind points, W1, W2, W3, and W4. The procedure involves obtaining estimated points Q1 and Q2 through linear interpolation in the V direction, followed by linear interpolation in the U direction to approximate point P. The velocity of any point in the wind field could be obtained by iterating the above procedure.
- (3) Representation. To present the spatiotemporal characteristics of the wind field in a 3D geographic scene, we use particles with life cycles to render the wind trajectory. Taking the purple trajectory as an example, each particle involved in this trajectory has an initial position (s_point), wind speed, and life cycle. Then, calculate the status of this particle at the next moment (n_point) based on the velocity and time, and update the corresponding wind speed in U and V directions as well. Finally, using streamline to render s_point and n_point and update the frame to generate wind trajectories.

2.4.4. Mechanical behavior modeling

A segment of the bridge structure is abstracted as a unit; all units form the bridge as a whole. Each unit is composed of its own node, which contains coordinate information, stress value information, cross-section information, and so forth. Different units can share the same

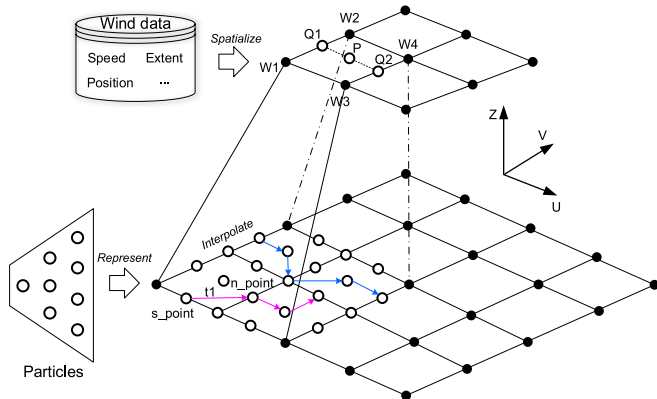


Fig. 6. The general process of wind field modelling based on bilinear interpolation and particle rendering.

node, and the data structure of the bridge stress model is shown in Fig. 7.

Then, we obtain each node's position and stress value by id, connect two certain unit nodes into a line segment in 3D space, and map the stress value into a line according to the gradient change to represent the stress state. According to this rule, all the cells are traversed sequentially until the modelling of stress line elements of the bridge structure is completed.

Finally, we perform a more intuitive spatial modelling of the stress behaviour of the bridge structure based on the line elements. Specifically, the stress simulation results contain the constitutive relationship between units and nodes, the position information of nodes, and the cross-section information corresponding to each unit node. Therefore, according to the characteristic that each unit has cross-section information, we take the line segment connecting the starting and ending nodes of the unit as the tensile path, refer to the idea of cross-section sampling, and use the colour interpolation method to draw the linear stress field model into a 3D body stress field model (Li et al., 2024). The specific process of modelling the bridge stress behaviour is shown in Fig. 8.

2.5. Visual representation of bridge construction by analogy with growth trees

The visual representation leaps forward the bridge construction from static drawings to vivid 3D scenes, which is vital in assisting decision-making (Li et al., 2021; Wu et al., 2022; Zhu et al., 2024a). Integrating environmental factors, construction schedules, and time dimensions into 3D scenes to simulate the bridge construction process in advance enables the constructors to pre-discover the potential issues and optimize the construction plan. This section will illustrate the ideas of visual representation of bridge construction.

2.5.1. Tree growth and bridge construction process analogy

Inspired by Ding's (2019) digital twin-based multi-scale modeling approach and reference to the Building Information Model Delivery Accuracy Standards, we analogy the bridge construction process to tree growth, as shown in Table 1.

Furthermore, Fig. 9 shows a schematic diagram of the analogy of the bridge construction process with tree growth.

The generative process describes as follows:

- (1) "Tree trunk" represents the main procedure of bridge construction from bottom to top.
- (2) "Tree fork" represents the key construction nodes BC_n (e.g., tower, deck system, tunnel anchorage) involved in "Tree trunk".

$$B = \{BC_1, BC_2, \dots, BC_n\} \bowtie R_t \bowtie R_m \quad (4)$$

B indicates the construction procedure in virtual space, which includes n key construction nodes $\{BC_1, BC_2, \dots, BC_n\}$ associated with the time relationship R_t and semantic relationship R_m . R_t denotes the construction sequence from bottom to top, R_m denotes the semantic relationship between nodes, also mentioned in Section 2.2.2.

- (3) "Tree branch" represents the bridge components in a specific node BC_1 (e.g., tower).

$$BC_1 = \{BD_{1,1}, BD_{1,2}, \dots, BD_{1,k}\} \bowtie R_t \bowtie R_s \bowtie R_m \quad (5)$$

In this case, $BD_{1,k}$ is a bridge component that will be automatically assembled based on the corresponding time relationship (R_t), spatial relationship (R_s), and semantic relationship (R_m) in the subsequent visual representation of bridge construction.

- (4) "Tree leaf" represents the corresponding 3D models and data.

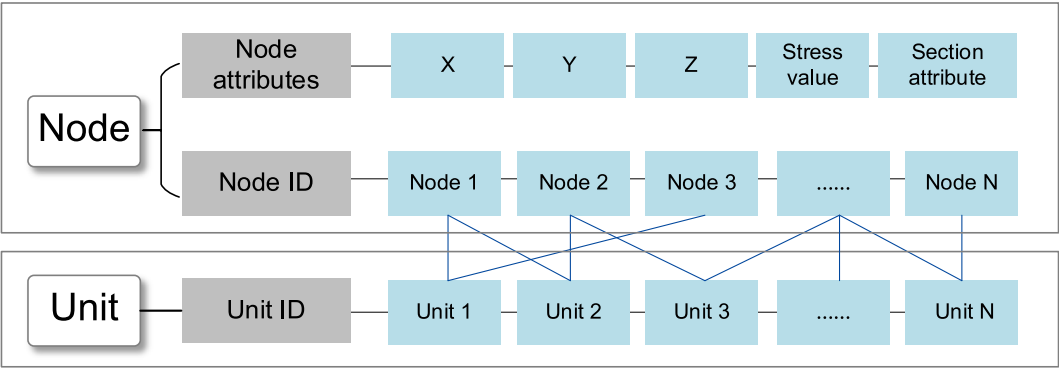


Fig. 7. The data structure of simulation results for bridge stress simulation.

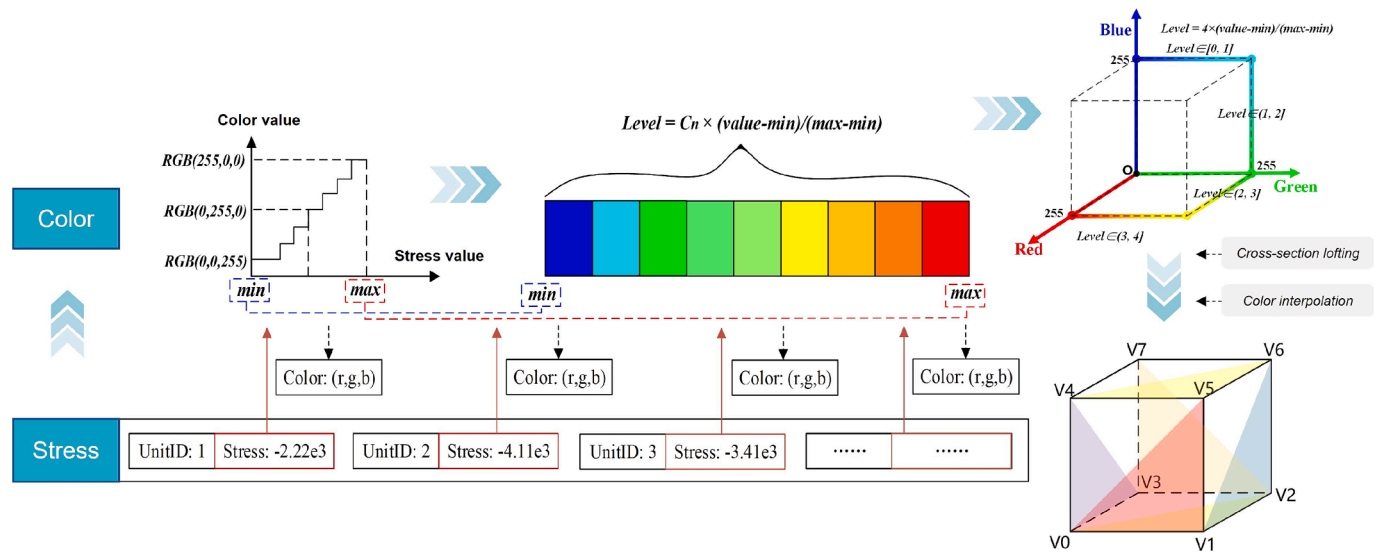


Fig. 8. The spatial modelling process for bridge stress behaviour.

Table 1
The comparison of the bridge construction process and tree growth.

No.	Tree growth	Construction process
1	Trunk	Main procedure
2	Fork	Key nodes
3	Branch	Bridge components
4	Leaf	3D model or data value

2.5.2. Visual representation for bridge construction

The bridge construction process can be decomposed into construction preparation, substructure construction, beam structure construction, and accessory structure construction. Each part contains many construction work steps, and the relevant models and elements involved in these steps have been organized in a tree structure, as described in Section 2.5.1. The task of this section is to represent these elements in 3D digital space according to a timeline, thus providing the visual representation of bridge construction from a geospatial storytelling-like perspective.

The schematic diagram of the visual representation workflow of bridge construction shows in Fig. 10. First, the bridge construction cycle and schedule map onto a timeline in digital space. Second, the 3D models of bridge components involved in different phases are scheduled to achieve 4D progress simulation. Third, the environmental factors in the bridge construction process are visualized to assist in optimizing the construction plan. Finally, camera tracking allows the visual

representation of bridge construction from multiple angles and an all-around perspective.

3. Experiment analysis

3.1. Study area and data description

This article selected a mega suspension bridge under construction as the study area for experiment analysis, as shown in Fig. 11. The bridge under construction is located in Luding County (29°55'32"N–29°56'03"N, 102°13'18"E–102°14'07"E), Sichuan Province, China, crossing the V-shaped valley of the Dadu River with a height difference over 800 m, a significant temperature difference of up to 38°C and down to –6°C. These complex topographic conditions and environmental factors pose an extreme challenge to bridge construction.

This article relies on three types of data: landscape data, bridge geometry models, and field simulation data. The landscape data includes satellite imagery, DEM and DSM, were collected from ArcGIS Map-Server, MapTiler terrain services, and drone-based photogrammetry, respectively. The DSM was subsequently converted into 3dtiles format to facilitate efficient web-based geovisualization. The bridge primitive models were created using the geometric and attribute parameters in the CAD design drawings and modeled using Bentley MicroStation. The resulting BIM models were likewise converted into 3dtiles format to enable seamless integration within the web-based visualization environment.

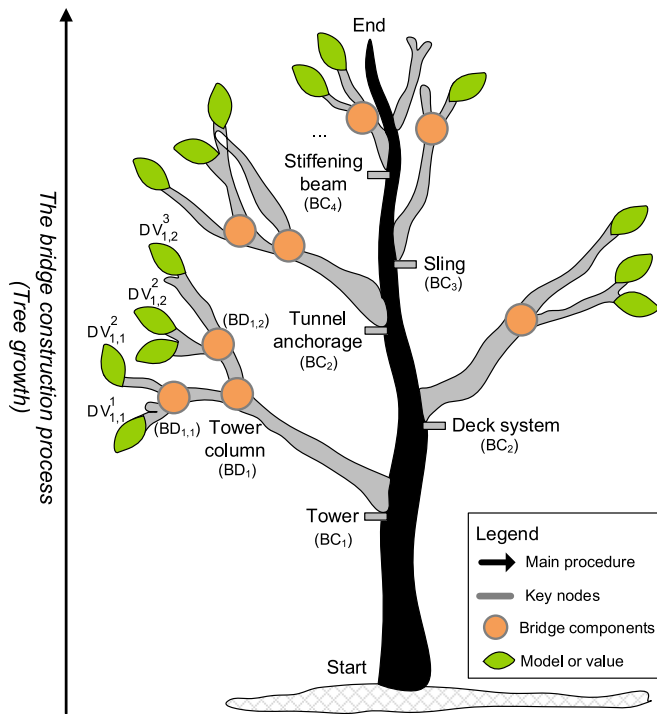


Fig. 9. The analogy of the bridge construction process with tree growth.

The field data were obtained through CFD simulations using the landscape data and bridge geometry models as input. Specifically, wind and temperature fields were simulated in ANSYS Fluent using the processed terrain and bridge geometry models as boundary conditions and computational domains. Bridge stress were calculated using Midas Civil based on the applied environmental loads derived from CFD results. The simulation outputs were exported as point-based datasets and subsequently subjected to spatial modeling and visualization within the GDT environment. A more detailed description is given in Table 2.

3.2. Prototype system implementation

Based on WebGL and 3D visualization technology, we developed a GDT-oriented prototype system with B/S architecture, which was utilized to perform the spatial modelling of the bridge environment and 3D

representation of bridge construction. Fig. 12 shows the interface of the system. The server side was built with Node.js v19.6.1, and the browser was Google Chrome 109.0.5414.120. The 3D rendering engine used an open-source library Cesium.js v1.96, and the interface was designed and built based on Vue.js v 3.3.0. The prototype system was run and tested on Lenovo Legion R9000P2021H. The processor was an AMD Ryzen 7 5800H with Radeon Graphics, 16 GB memory, and NVIDIA GeForce RTX 3060 Laptop GPU 6 GB.

3.3. Simulation results of physical field and mechanical behavior

3.3.1. Simulation results of temperature and wind field

Taking one steel truss beam as an example, Fig. 13 (a) shows the numerical simulation results of the temperature field. The grid size is $0.1 \text{ m} \times 0.1 \text{ m} \times 0.1 \text{ m}$, and the number of temperature points is 72,360 before spatiotemporal interpolation, with each point corresponding to a single temperature value. The computational domain for the wind field simulation was defined as a rectangular region measuring $1000 \text{ m} \times 1500 \text{ m} \times 500 \text{ m}$, centered on the bridge. The final computational mesh comprised approximately 2.6 million elements. Considering the canyon topography and the actual meteorological conditions of the study area, the inlet and outlet boundaries were defined according to the prevailing wind direction. The simulation was conducted until the residual error converged below 0.0001, resulting in the numerical simulation of the canyon wind field around the target mountainous bridge area, as shown in Fig. 13 (b).

3.3.2. Simulation results of bridge stress under wind-temperature coupling effects

In addition to independently simulating the temperature and wind fields, we also investigated the interaction between temperature, wind, and structural behavior, specifically the variations in bridge stress under coupled wind and temperature effects. First, we analyzed the changes in bridge stress under temperature variations of $\pm 20^\circ \text{C}$, corresponding to a 20-degree decrease and a 20-degree increase, as shown in Fig. 14. Fig. 14(a) and (b) reveal distinct stress distribution patterns at the bridge tower and stiffening beam, demonstrating that substantial temperature variations significantly influence the bridge structure.

Second, we examined the variations in bridge stress under different lateral wind loads, as shown in Fig. 15. Fig. 15(a) and (b) illustrate the stress distribution of the bridge under lateral wind loads of 3 KN/m^2 and 6 KN/m^2 , respectively. The results indicate that the stress response of the bridge tower increases markedly with higher lateral wind loads, with

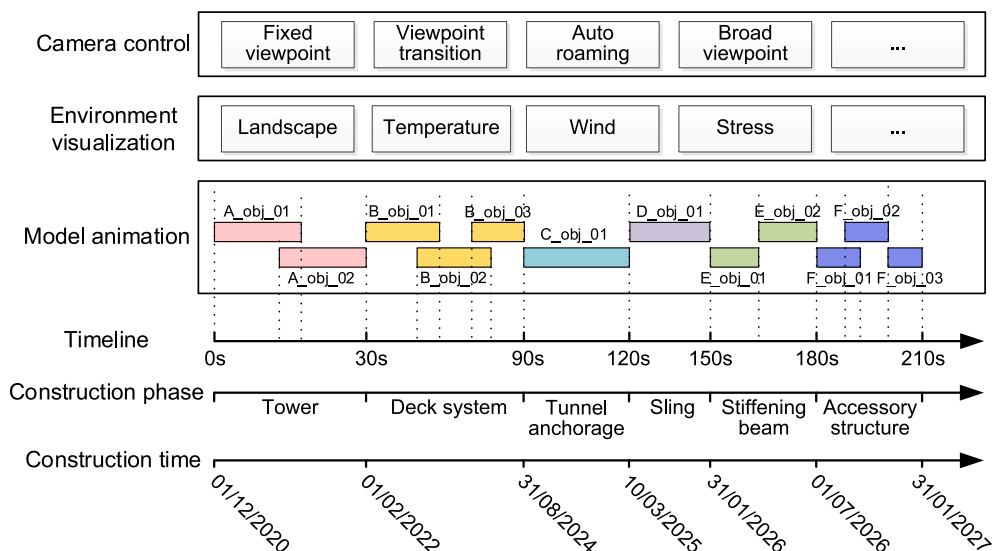


Fig. 10. The workflow of visual representation for bridge construction.

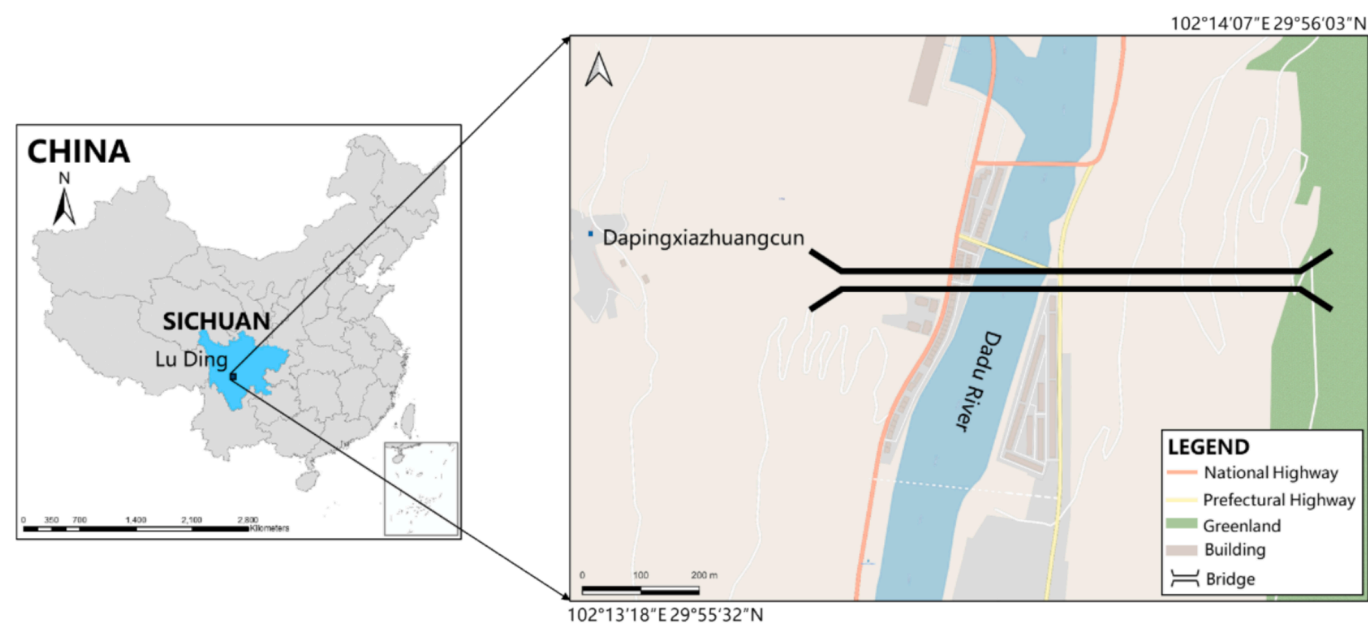


Fig. 11. Study area: a mega suspension bridge under construction in Luding.

Table 2				
The description of data involved in the experiment.				
No.	Type		Format	Source
1	Landscape data	Satellite image	png	ArcGIS MapServer
		DEM	terrain	Maptiler
		DSM	3dtiles	Drone
2	Bridge geometry models	BIM	3dtiles	Bentley MicroStation
3	Field simulation data	Wind	point	Ansys Fluent
		Temperature	point	Ansys Fluent
		Stress	point	Midas Civil

significant stress concentrations occurring at the tower base and at the intersections between the main tower and crossbeams.

Third, we investigated the variations in bridge stress under coupled wind–temperature effects, specifically analyzing the stress distributions when the temperature decreased by 20 °C with a wind load of 3 KN/m², and when the temperature increased by 20 °C with a wind load of 6 KN/m², as shown in Fig. 16.

To further clarify the variation patterns of bridge stress distribution under wind–temperature coupling, excluding dead loads and other external forces, we recorded the maximum stress changes at critical points of the cable tower (the connection between the tower and the crossbeam) under different combinations of temperature and wind loads. The results, summarized in Table 3, show that the stress values exhibit an approximately linear increase with rising temperature and increasing wind pressure intensity. In summary, analyzing the effects of varying wind and temperature loads on structural stress can provide valuable guidance for construction. Such simulations can help optimize design parameters, enhance structural safety, and support decision-making during the construction process.

3.4. Spatial modeling and representation of bridge environments

3.4.1. Large-scale environment landscape representation

Fig. 17 shows the representation of the environmental landscape surrounding the bridge construction, which DEM, satellite images, and DSM integrate. The overlay of DEM and satellite images for a large-scale

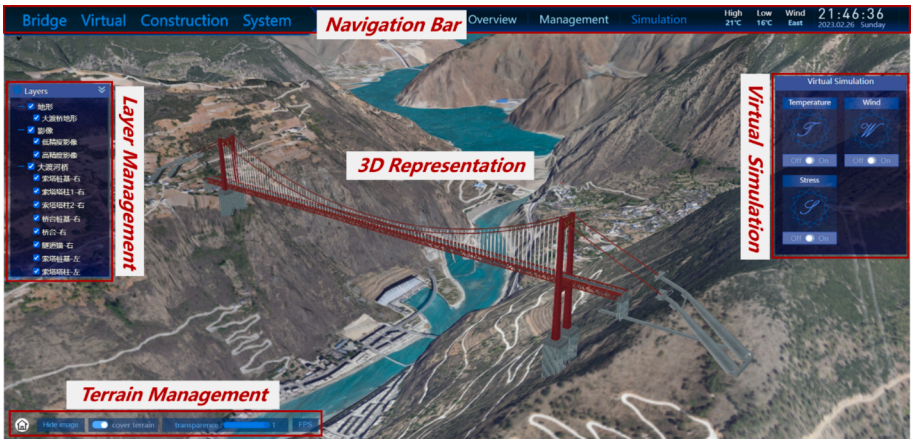


Fig. 12. The interface of the prototype system. The prototype system comprises five main parts: Navigation Bar, Layer Management, 3D representation, Virtual simulation, and Terrain Management. The Navigation Bar is used to initialize the system, the Layer Management controls the visibility and renders the order of layers, the 3D representation provides the visualization of the bridge and landscape, the Virtual Simulation allows field modelling and expression, and the Terrain Management adjusts the scene transparency.

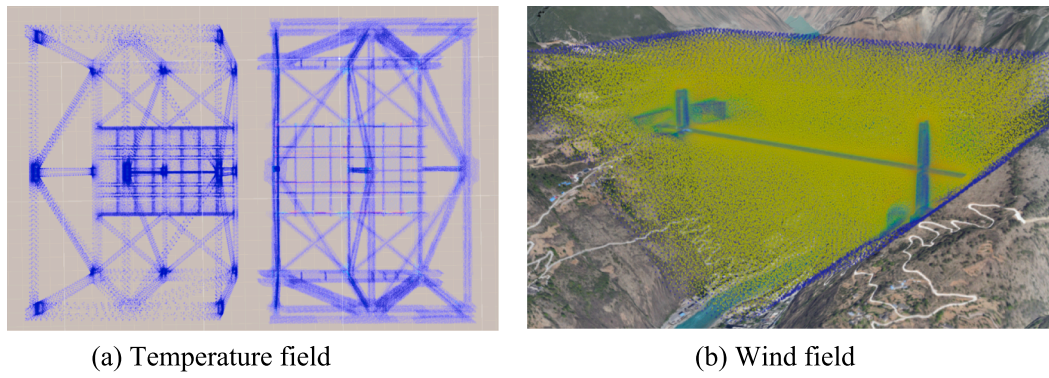


Fig. 13. Numerical simulation results of temperature and wind field.

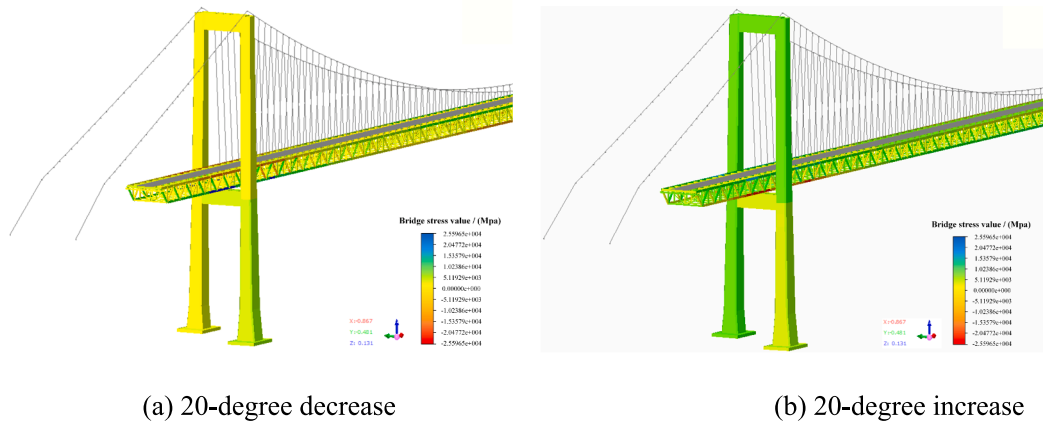


Fig. 14. Comparison of stress distribution with 20-degree temperature decrease and increase.

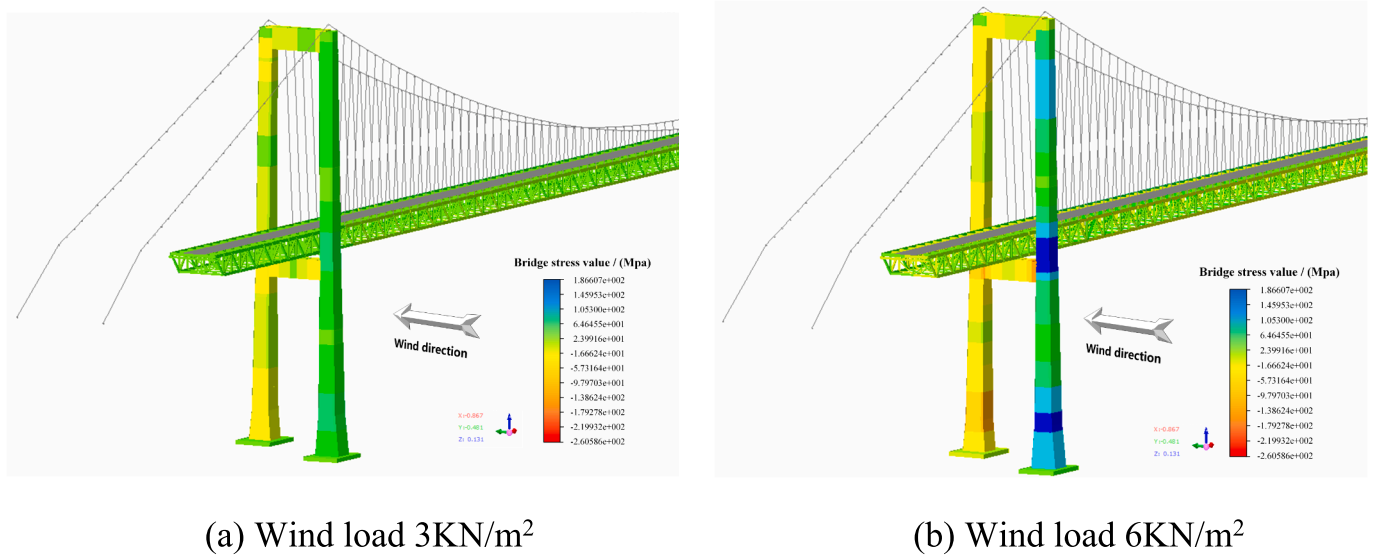


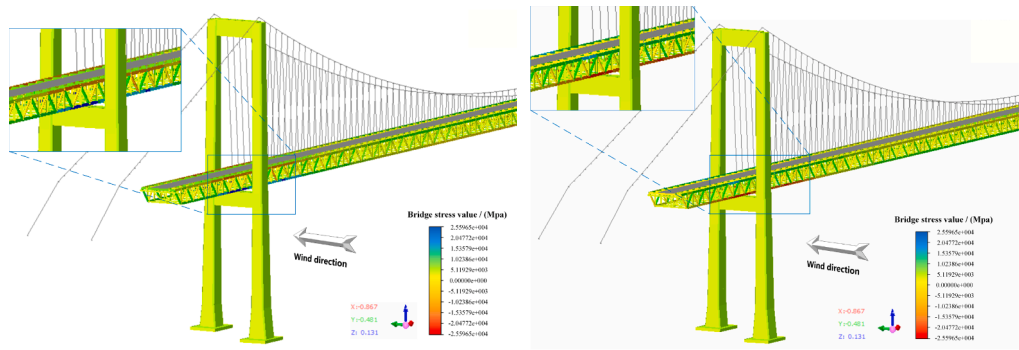
Fig. 15. Comparison of stress distribution with different lateral wind loads.

terrain rendering, and the other is the DSM used to represent more detailed environmental information around the bridge construction. To improve the rendering efficiency, we use the 3D Tiles data structure to organize the DSM landscape data involved in our case.

3.4.2. Generation of bridge scenes in 3D

As mentioned in Section 2.4.2, the bridge consists of many primitive

models encoded into a top-down directory tree. Each primitive model comprises data properties and object properties. The data properties include the model's ID, position, orientation, and attributes, while the object properties consist of semantic, spatial, and time relationships. The three relationships mentioned above control the hierarchy, spatial location, and display time of the primitive model, respectively, which enables the automatic generation of bridge scenes in 3D, as shown in



(a) 20-degree decrease with wind load 3KN/m² (b) 20-degree increase with wind load 6KN/m²

Fig. 16. Comparison of stress distribution under different wind-temperature coupling effects.

Table 3
Changes of bridge stress distribution under wind-temperature coupling.

Temperature	Stress			
	Wind			
	0	2	4	6
0	0.0	29.2	60.5	93.9
5	31.5	64.8	101.4	141.2
10	63.2	100.9	143.5	190.0
15	95.1	137.6	186.7	240.5
20	127.3	175.1	231.1	292.8

Fig. 18.

3.4.3. Temperature and canyon wind representation

Fig. 19 shows the spatial modelling and representation of temperature results, where sparse monitoring points generated the temperature field around the bridge by AIDW interpolation. In addition, we simulated, modeled, and represented the temperature of the bridge towers under daylight at three different times of the day. The maximum difference at the top of the tower can exceed 20°C. The modeling and representation of the temperature field help the constructors focus on temperature-sensitive bridge structures.

Fig. 20 illustrates the wind field around the bridge from various directions in a virtual geographic environment. This can aid constructors in intuitively comprehending CAE-based wind simulation results and the spatial relationship between topography, bridge, and wind. The

representation of wind direction and speed in a virtual geographic environment is advantageous for mitigating the potential risks associated with wind loads during bridge construction.

3.4.4. Bridge stress representation

Fig. 21 shows the stress status of the bridge at different levels of detail. Fig. 21(a) presents the line stress of the bridge, while Fig. 21(b) further demonstrates the face stress of the bridge components. Fig. 21(c) gives a more detailed representation of solid stress for the bridge structure. The LOD modeling of stress can meet the requirements of bridge construction in different stages but also the rendering efficiency of the virtual scene.

3.5. Visual representation of the bridge construction process

The visual representation was developed based on a timeline that dynamically presents the virtual construction process of the bridge, with the bridge growing from the substructure to the superstructure, as shown in Fig. 22. Through visual simulation, stakeholders can gain a better insight of the construction process. This simulation also helps decision-makers verify the feasibility and reliability by comparing the design scheme and construction progress, thus forming a stable construction procedure.

4. Discussion

Following the concept of GDT, an innovative spatial modelling



Fig. 17. 3D representation of large-scale environment landscape surrounding the bridge construction.

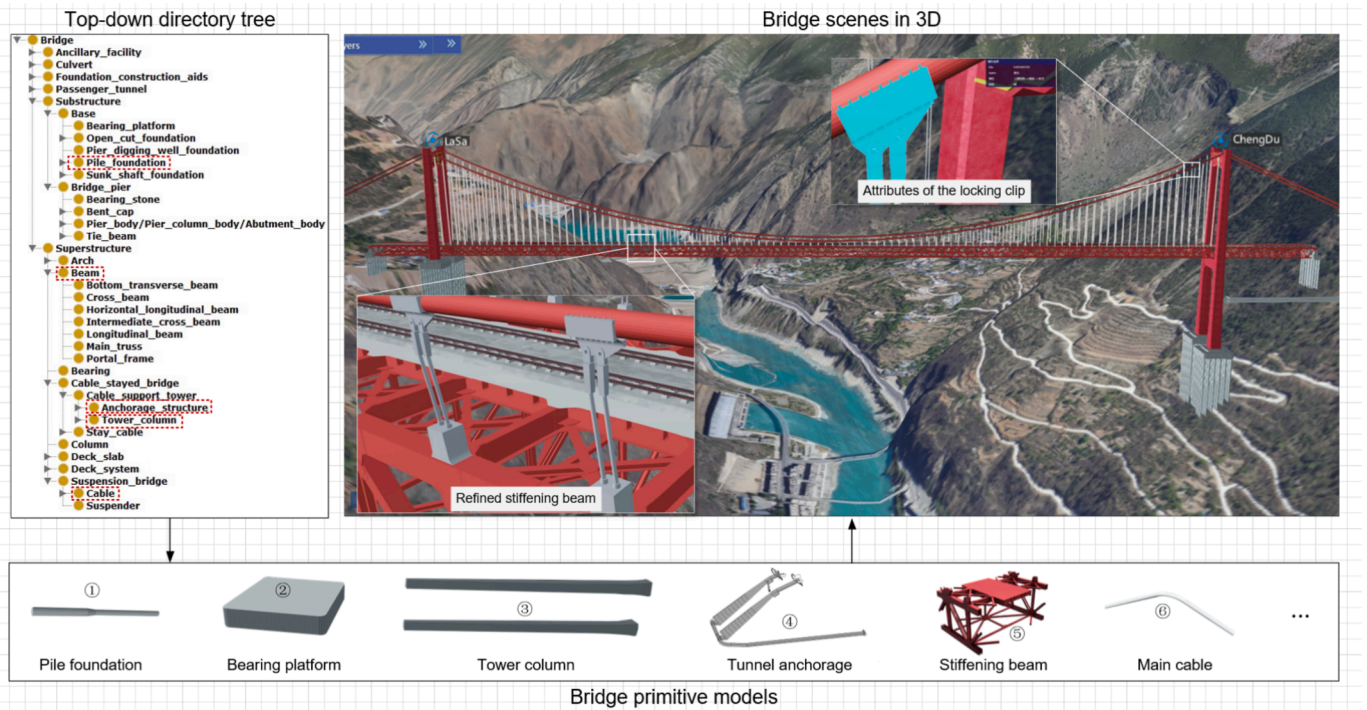


Fig. 18. The virtual bridge scene in 3D.

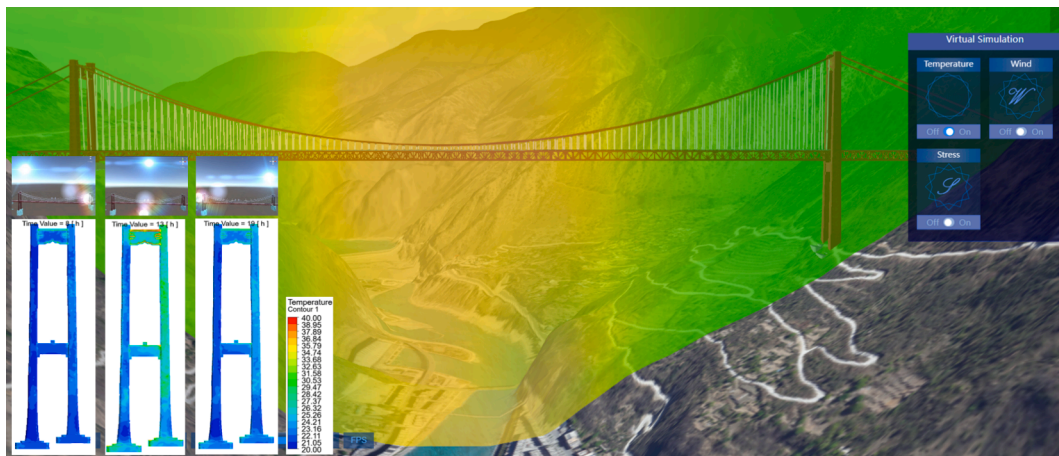


Fig. 19. Temperature modelling and representation. The left side shows the temperature change of the bridge tower during the morning, noon, and afternoon.

approach for bridge construction environments is proposed. Here, we highlight the key findings and limitations associated with the proposed approach.

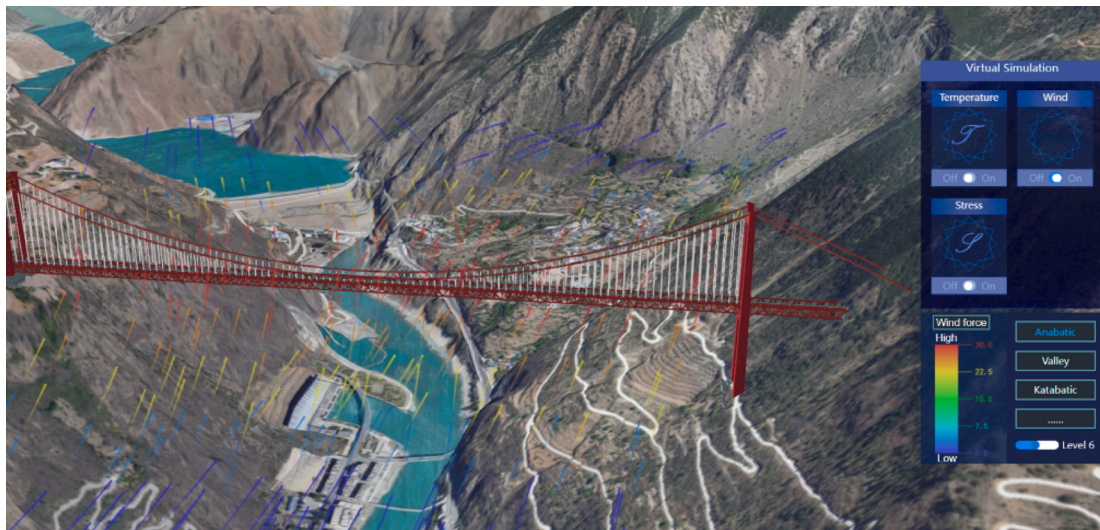
4.1. Principal findings

Design and implementation of a GDT-oriented spatial modelling framework of bridge construction environments. The proposed framework synthesizes methodologies from conceptual modeling, numerical simulation, spatial modelling, and multi-dimensional visualization to enable a comprehensive representation of bridge construction environments. The logic model clarifies the crucial objects and relationships, providing a reference guide for spatial modelling. The numerical simulation reveals variations in mechanical behavior under the influence of environmental factors. Spatial modelling enables the mapping of bridge construction from the physical environment to virtual geographic space. Multi-dimensional visual representation provides a digital window for

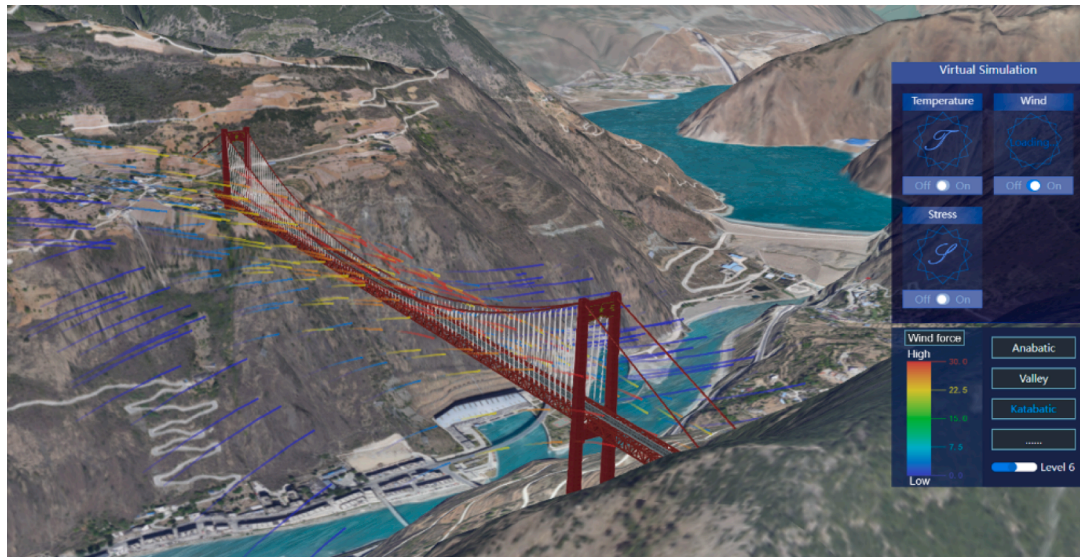
stakeholders to perceive and understand the bridge construction. The integrated approach advances the GDT from concept to system implementation and primary application, promoting intelligent bridge construction development.

Mechanical behavior simulation under wind-temperature coupling effects. We not only simulate the temperature and wind fields within the bridge construction environment but also incorporate stress simulations that account for coupled wind-temperature effects. This approach moves beyond a simple superposition of multiple simulation data types and instead reveals the intricate interactions among wind fields, temperature, and structural mechanical behavior. Analyzing the effects of varying wind and temperature loads on structural stress provides valuable insights for construction planning. Such simulations can aid in optimizing design parameters, enhancing structural safety, and supporting informed decision-making throughout the construction process.

Multi-dimensional visual representation serves as a digital window to perceive, understand, and manage the bridge construction. Drawing



(a) Anabatic wind



(b) Katabatic wind

Fig. 20. The wind field around the bridge from various directions. (a) Anabatic wind: a “moving upward” warm wind which blows up a steep slope, driven by heating of the slope through insolation. (b) Katabatic wind: down-slope wind, opposite to the anabatic wind.

an analogy between bridge construction and tree growth, we simulate the generation of pile foundations, deck systems, stiffening beams, and other structures in digital space in advance. This intuitive and dynamic 3D scene fosters effective interaction and communication between decision-makers, designers, and constructors involved in bridge construction. Additionally, advanced construction simulation and representation enable the evaluation of construction feasibility by comparing the design scheme with actual progress, thereby facilitating the optimization of the construction plan.

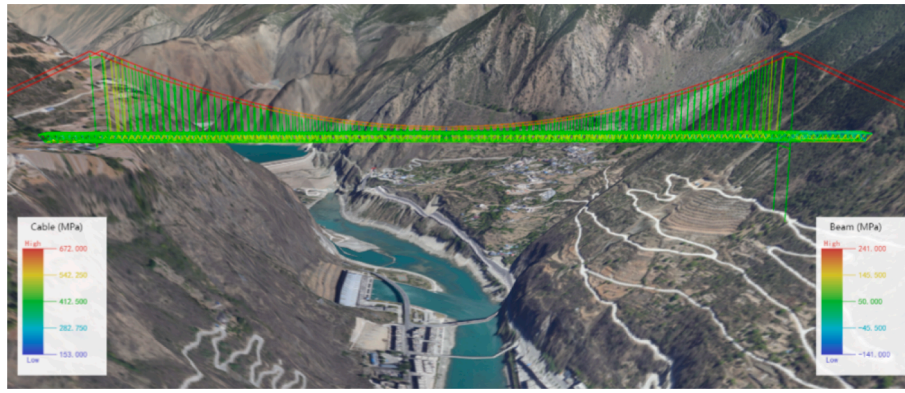
5. Limitations

For additional inspiration to consider, the limitations of this study are discussed below.

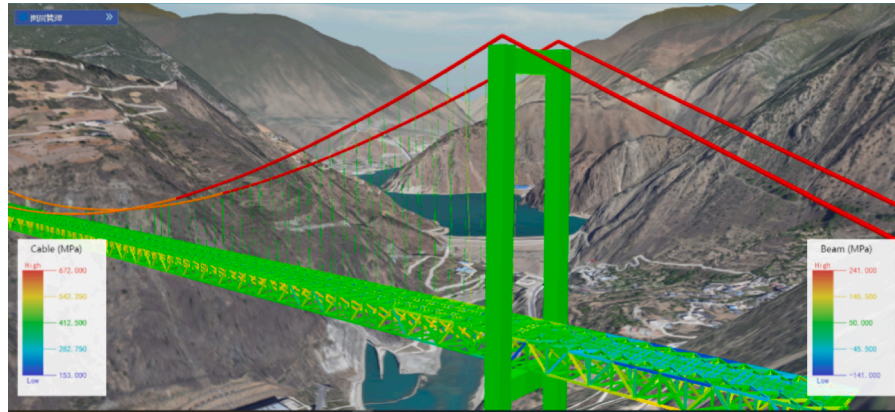
- (1) The simulations of temperature, wind fields, and structural stresses are currently performed using commercial software (e.g., ANSYS). However, due to licensing restrictions, direct integration with our bridge virtual construction system is not feasible. In the

current implementation, numerical simulations are conducted offline and subsequently imported into the GDT environment for spatial modeling and visualization. To overcome this limitation, we are considering the use of open-source finite element analysis libraries, such as FreeFEM, to simulate environmental fields and mechanical behavior on the server side. This approach will enable the development of a comprehensive workflow that seamlessly integrates data processing, numerical simulation, and visual representation, thereby supporting real-time simulation of the bridge construction process.

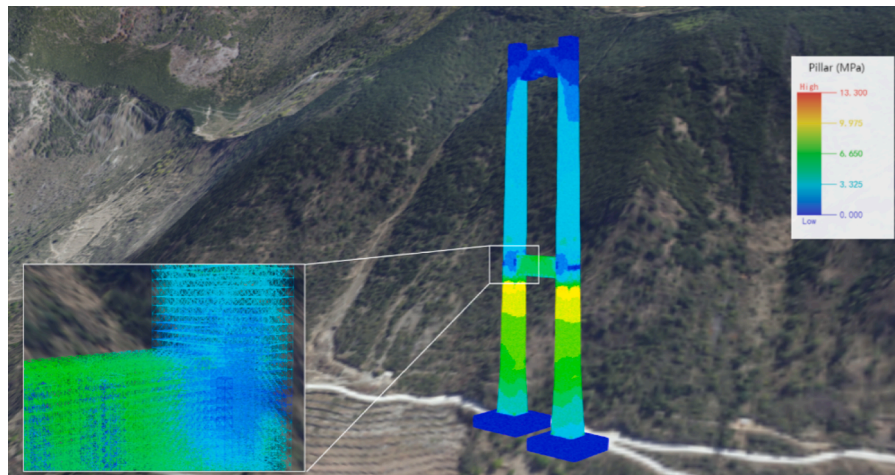
- (2) This study does not yet incorporate predictive algorithms for the environmental and mechanical behavior of bridges, resulting in an incomplete feedback loop between the physical and virtual geographic environments, which is closely associated with the lack of access to sensor data. Therefore, our future work will focus on establishing two-way mapping and communication mechanisms, as well as enhancing the predictive capabilities at the core of the geospatial digital twin (GDT). By leveraging the digital twin virtual environment to guide and optimize on-site bridge



(a) Line stress representation



(b) Surface stress representation



(b) Solid stress representation

Fig. 21. The stress status of the bridge at different levels of detail.

construction, we aim to achieve genuine “virtual-to-real” control within the GDT framework.

- (3) The experimental case area selected for this study is a complex mountainous region. Therefore, our methods and experiments primarily focused on wind and temperature fields, the two main physical environmental fields. However, if bridges are constructed in an oceanic environment, wave fields must also be taken into consideration. In the future, we will further deepen our research into various physical fields of the environment to broaden the application scenarios. The integration of such

additional features will be smoothly integrated using the CityGML standard as explained in the next subsection.

5.1. Vision

While the proposed model also lays the groundwork for a broader framework supporting the integration of construction objects and their environmental elements for accurate simulations and post-deployment maintenance, the implementation of such a complete framework is

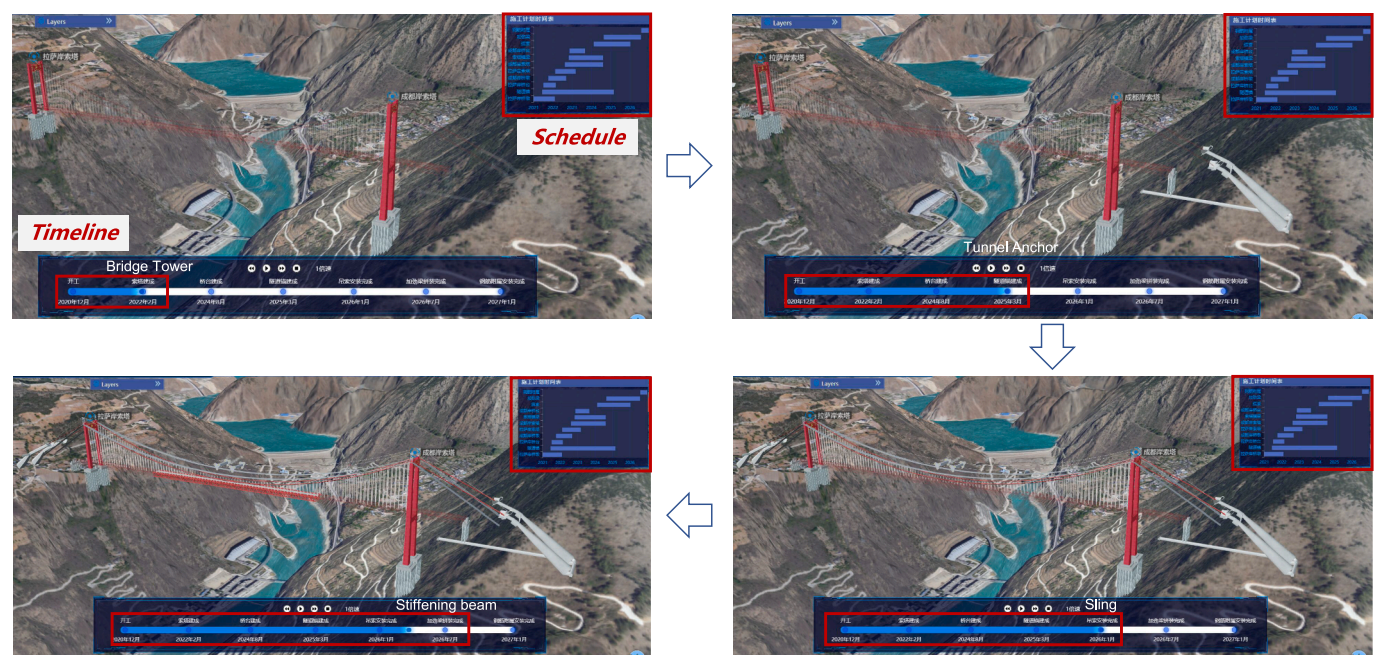


Fig. 22. The visual simulation and representation of the bridge construction process.

beyond the scope of the present article. Consequently, the framework-level integration is discussed at a conceptual level only, with the focus placed on validating the suitability of the proposed data structure.

To support the proposed GDT-oriented spatial modelling approach in a standardized manner, CityGML is adopted as the underlying data model for representing bridge construction environments. CityGML defines a conceptual model and an exchange format for the representation, storage, and exchange of virtual 3D city models (OGC, 2012), and

therefore provides a robust and widely accepted foundation for structured spatial data integration. Fig. 23 illustrates the modular organization enabled by CityGML, which supports the coherent integration of spatial, semantic, and temporal information across multiple thematic domains.

In our proposed model, the CityGML Core, Generics, Dynamizer, Bridge, and Relief modules are regarded as mandatory components. The Core module provides the fundamental concepts required for

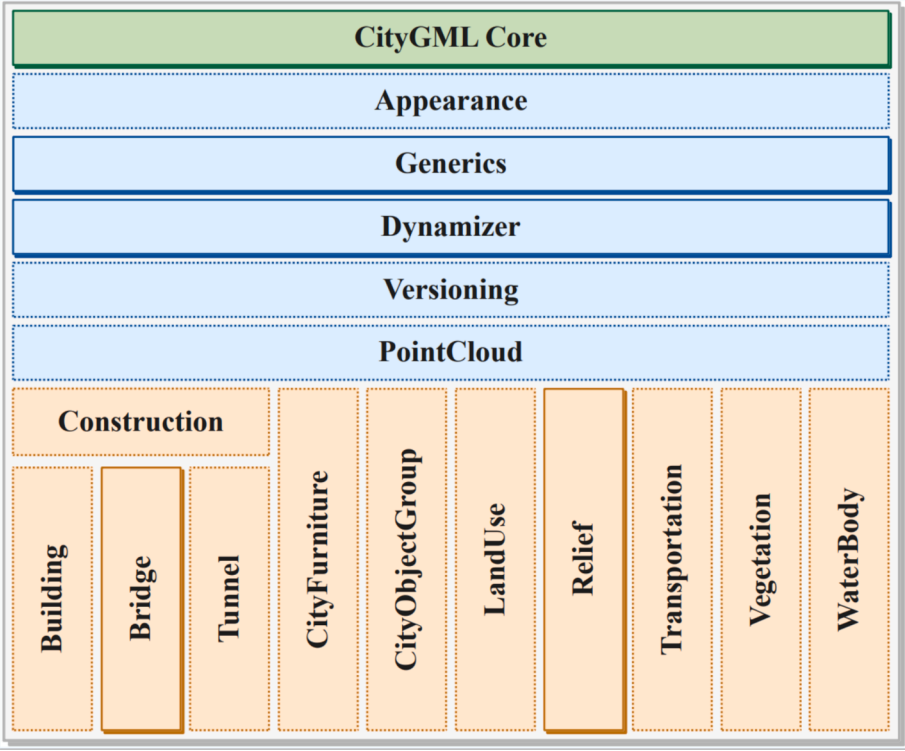


Fig. 23. Overview of the CityGML 3.0 module structure. For the bridge use case, the relevant and mandatory thematic modules (vertically shaded boxes) and the corresponding applicable thematic modules (horizontally shaded boxes) are highlighted. The dotted boxes are facultative for our bridge use case. This Figure is) adapted from Kutzner et al. (2020).

representing city objects, geometries, and spatial reference systems. The Generics module is used to accommodate application-specific objects and attributes that are not defined within standard CityGML schemas. In this study, it enables the representation of environmental fields such as wind and temperature, as well as waves and currents in scenarios where bridge components interact with water bodies.

The Dynamizer module plays a key role by enabling the linkage of time-varying properties, derived from numerical simulations or real-time sensor data to city objects. This capability is essential for supporting construction-stage simulations and monitoring processes. The Bridge module is required to represent the bridge structure itself and its hierarchical components, while the Relief module is indispensable for modelling the surrounding terrain, which directly influences environmental conditions and construction activities. Fig. 24 shows the conceptual integration of dynamic simulation and sensor data within the CityGML-based model, adapted from Chaturvedi and Kolbe (2016).

In addition to the mandatory modules, the Versioning module supports the management of multiple temporal states of city objects, such as planned, under-construction, and as-built representations of bridge components. Several optional CityGML thematic modules may be incorporated to enhance visual realism and simulation detail where required. The Transportation module can represent roads and railways connected to the bridge, while the WaterBody module enables the modelling of rivers, reservoirs, or marine environments relevant to bridge construction. The Vegetation module enhances landscape representation and may contribute to wind-field simulations, and the CityFurniture module allows the inclusion of site-level objects such as temporary installations or urban furniture. Furthermore, modules such as Tunnel and Building can be integrated in extended scenarios where bridge construction interacts with subsurface infrastructure or adjacent urban environments.

6. Conclusion

The GDT represents an integration of the informational, physical and geographical domains to bridge the real and virtual worlds, offering a new perspective for intelligent bridge construction (Wu et al., 2021). In this context, we proposed a GDT-oriented spatial modelling approach of

bridge construction environments to assist in upgrading intelligence in construction. The main contributions of this article are summarized as follows.

At the theoretical level, in accordance with the connotation of the GDT, we developed a GDT-oriented spatial modeling framework that integrates conceptual modeling, numerical simulation, spatial modeling, and multi-dimensional visualization to achieve a comprehensive representation of bridge construction environments. This research not only provides methodological guidance for addressing the complexities of multi-field coupling and geospatial modeling of environments in bridge construction but also enriches the theoretical foundation of digital twin applications in GIS domains.

At the application level, we developed a bridge virtual construction system that comprehensively considers environmental factors, mechanical behavior, and the entire construction process. This system was successfully applied to a major suspension bridge project currently under construction. The results show that the numerical simulation, spatial modelling and visual representation of bridge construction provide an effective solution for pre-discovering risks, optimizing construction plans, and assisting decision-making, which also has strong potential for the lifecycle management of bridge construction. More importantly, the proposed method is firmly grounded in the GDT concept, offering new insights and guidance for building GDT-oriented virtual geographic environments.

CRediT authorship contribution statement

Weilian Li: Writing – original draft, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Jun Zhu:** Writing – review & editing, Validation. **Jinbin Zhang:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization. **Jianlin Wu:** Supervision, Software. **Qing Zhu:** Supervision, Resources, Formal analysis. **Youness Dehbi:** Resources, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

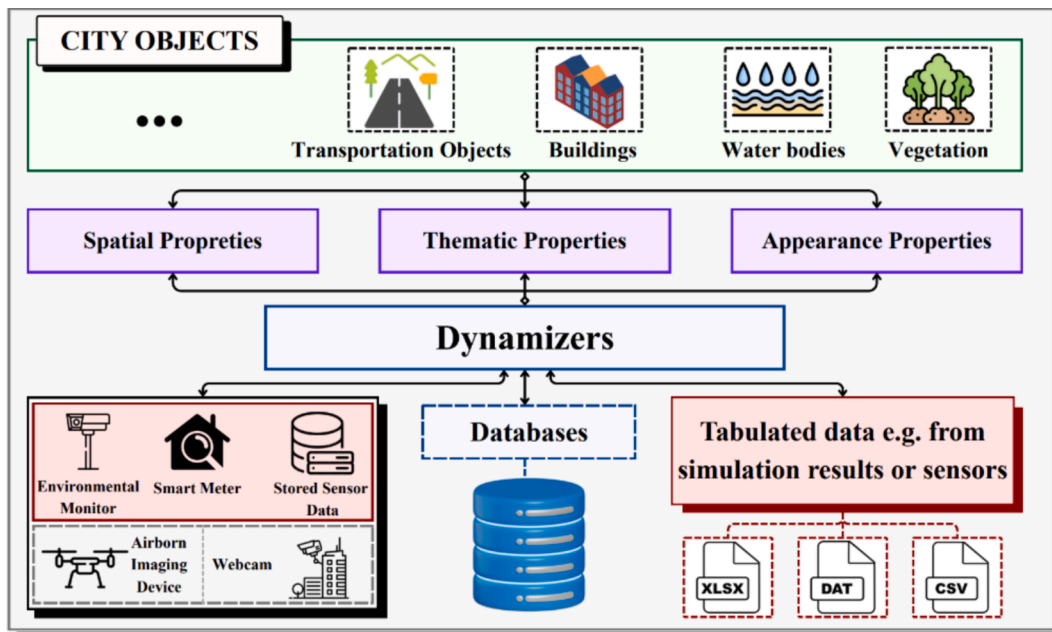


Fig. 24. Dynamizers for modelling dynamic behaviours of city objects by overriding their static values, and representing time-dependent values from sensors, simulation-specific databases, and external files. Highly relevant parts for our study are highlighted with red boxes. This Figure is adapted from Kanishk and Kolbe (2016).

the work reported in this paper.

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Data availability

Data will be made available on request.

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