Application of 3D Visualization Intelligent System in Geotechnical Engineering Investigation and Design

Gu NIE

No. 812 Geological Team of East China Metallurgical Geology & Exploration Bureau, Tongling, Anhui, 244000, China

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Abstract: The understanding of stratigraphic structure, site conditions, and construction impacts in geotechnical engineering projects has long been limited by fragmented data, two-dimensional representations, and professional segregation. This hinders the formation of a unified understanding and effective decision-making in investigation and design, leading to delayed risk identification and cost control. 3D visualization intelligent systems integrate investigation, design, and construction data, intuitively presenting subsurface spatial morphology and uncertainty distribution. They support scheme comparison, risk front-loading, and collaborative management, thereby enhancing design quality and implementation efficiency. This paper constructs the architecture of a 3D visualization intelligent system for engineering investigation, proposes a multi-source data acquisition and fusion process, establishes methods for geological model and parameter field representation, conducts stability and deformation analysis, and combines construction simulation and monitoring feedback loops. This achieves systematic application in information integration, collaborative design, and risk control.

1. Introduction

Urban space is developing in depth and density, accompanied by an increase in deep excavations, ultra-long tunnels, and projects in complex strata. Traditional expression methods based on point boreholes and 2D profiles struggle to fully reflect heterogeneity and the continuous variation of structures. Information discontinuity between investigation, design, and construction also frequently occurs. Consequently, schedule and cost deviations, delayed risk identification, and inefficient cross-disciplinary collaboration have gradually become key factors restricting project quality and safety. 3D visualization intelligent systems, using spatio-temporally integrated data as a carrier, couple multi-source observations, test results, and engineering parameters to intuitively present subsurface media and associated uncertainties. This supports scheme comparison, change management, and monitoring feedback loops. For geotechnical engineering, establishing a traceable, updatable, and predictive investigation and design system has become both necessary and feasible. This paper aims to propose a holistic application path for practical engineering, covering system architecture, data fusion, geological model and parameter field representation, computational analysis, and linkage with construction simulation and monitoring.

2. Significance of 3D Visualization Intelligent System in Geotechnical Engineering Investigation and Design

2.1 Enhancing Understanding and Design Decision Quality

3D visualization intelligent systems integrate data from boreholes, geophysical exploration, tests, and monitoring generated during the investigation phase onto a single platform. Replacing scattered 2D drawings and textual descriptions with intuitive 3D representations of geological bodies and key parameters facilitates a consistent site understanding among all project stakeholders[1]. Conducting scheme comparison and sensitivity analysis based on a unified model allows for earlier

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identification of unfavorable factors such as weak interlayers, abrupt stratum changes, and high water tables. This provides intuitive basis for key decisions regarding support types, dewatering layouts, excavation sequences, etc., reducing deviations caused by excessive conservatism or partial value selection. The system can express uncertainties as ranges or scenarios and dynamically update them in conjunction with monitoring data, ensuring design assumptions align with field performance and optimizing parameter selection and safety factor settings. Through this process, justification evidence becomes transparent, communication costs are reduced, design decisions become more traceable and verifiable, ultimately enhancing the completeness of investigation understanding and the reliability of design conclusions. This is suitable for daily application and promotion in various types of geotechnical engineering projects.

2.2 Building Data Closed-Loops and Collaborative Mechanisms

If data from different stages cannot be consolidated onto a common platform, it is difficult to support continuous engineering decision-making. Starting from this point, 3D visualization intelligent systems establish unified standards and coordinate frameworks, continuously aggregating data from investigation, design, construction, to operation and maintenance, forming a "collection → modeling → analysis →feedback → re-optimization" closed-loop. Boreholes, geophysical surveys, lab/field tests, monitoring points, and construction logs are automatically matched by time and space. Parameter changes are immediately flagged in the model with version records, ensuring clear rationale and traceable responsibility. Calculations for loads, seepage, and deformation during the design phase are compared against field monitoring curves; deviations exceeding limits trigger warnings, prompting support optimization or construction pace adjustments. Revised parameters subsequently update the database, forming a transferable knowledge base. In terms of cross-disciplinary collaboration, geotechnical, structural, and MEP disciplines can locate issues and check conflicts within the same 3D context, reducing information distortion and redundant modeling[2].

2.3 Cost Reduction, Efficiency Improvement, and Front-Loaded Risk Control

3D visualization intelligent systems front-load cost and risk management to the investigation and scheme demonstration stages. Through 3D integration of borehole, geophysical, and test results, weak zones, water inflow channels, and areas affecting sensitive structures are identified. This allows for optimization of support levels, dewatering/drainage layouts, and excavation sequencing, reducing design changes and rework. Relying on the unified model, automatic quantity take-off and parametric comparison are conducted, quantifying material consumption, critical paths, and equipment usage, providing verification basis for budget design and procurement decisions. Key construction processes and site logistics are simulated before construction, clarifying impact windows on surrounding structures and utilities, accompanied by setting monitoring sections and alarm thresholds, establishing an early warning → response→ review mechanism. During construction, monitoring data fed back into the model enables dynamic correction of parameters and boundary conditions, avoiding redundant investment due to excessive safety margins while maintaining effective risk control.

3. Main Challenges of 3D Visualization Intelligent System in Geotechnical Engineering Investigation and Design

3.1 Dispersed Information

Information dispersion is mainly reflected in multiple data sources, varied formats, delayed updates, and semantic inconsistencies. Exploration boreholes, geophysical profiles, sampling and testing, monitoring records, and construction logs are generated by different units and personnel. Inconsistent coordinate datums, coding systems, and accuracy standards lead to divergent records and redundant descriptions of the same stratum or parameter across different sources[3]. The lack of machine-readable links between 2D drawings and text reports prevents direct correlation to spatial locations and time points, resulting in fragmented "point evidence." Weak version management makes historical modifications untraceable, and local revisions often occur without the overall context. Handovers between stages often involve missing pages, items, or simplification, where raw data is compressed into conclusive statements, making it difficult for subsequent design to verify sources. Furthermore, dynamic information generated during monitoring and construction is difficult to incorporate into the investigation understanding system in a timely manner, leading to a disconnect between design basis and field conditions.

3.2 Inadequate 3D Representation

Existing data is mostly presented in 2D profiles, single borehole logs, and discrete measurement points, making it difficult to reflect the true morphology of undulating stratum interfaces, the continuity of weak interlayers, and fracture structures. Local extrapolation often results in oversimplification or unreasonable splicing. The lack of unified coordinate and scale transformation among multiple geophysical and test results prevents accurate alignment of different data sources in 3D space, often leaving volumetric models superficial. Geotechnical parameters are given in tables or zonal averages, making it difficult to associate them with spatial grids; parameters like permeability coefficients and strength indices cannot form continuous fields, limiting subsequent analysis boundaries and load descriptions. The temporal variations of groundwater levels and aquifer structures are often represented by static surfaces, unable to reveal dynamic responses under seasonal changes or construction disturbances. The spatial position accuracy of utilities, foundations, and existing structures is insufficient or missing, obscuring the spatial relationship between engineering elements and geological bodies, making it difficult to identify conflict risks early within a 3D context.

3.3 Difficulties in Cross-Disciplinary Collaboration

Difficulties in cross-disciplinary collaboration are centrally manifested in unclear information boundaries and insufficient model interoperability. Disciplines such as geotechnical, structural, plumbing, MEP, and transportation use their own software and coding systems. Inconsistent data formats, coordinate datums, and naming conventions make seamless model integration difficult, requiring frequent reconfirmation of interface conditions. Professional deliverables are mostly submitted as static drawings or reports, lacking directly usable spatial data and parameter descriptions. Review comments and modification records are scattered across emails and attachments, making version sources difficult to verify. Clash detection and impact analysis are often conducted late, with inconsistencies in initial assumptions leading to design iterations and schedule delays. The update pace between field changes, monitoring information, and the design model is mismatched; some disciplines work based on outdated information, causing decision-making delays.

3.4 Uncertainty Propagation and Amplification

Uncertainty propagation and amplification primarily stem from the layering of data sources, parameter selection, and model assumptions. Sparse investigation points lead to significant spatial extrapolation errors for stratum interfaces and weak interlayers. Test indices are affected by sampling disturbance and differences in testing methods, lacking stability in statistical distribution. These uncertainties become embedded and propagate during mesh generation, boundary setting, and load input within the 3D model. Inconsistent value selection criteria used by different disciplines in aspects like seepage, strength reduction, and load case combinations make it difficult to trace the source of coupled errors[4]. Construction disturbances and groundwater temporal variability are not promptly reflected, and delays or missing monitoring data further amplify prediction deviations. Opaque version updates and missing metadata lead to the perpetuation of parameter usage, where local conservatism or radicalism in value selection evolves into systematic bias through multiple iterations, ultimately manifesting as imbalanced safety margin allocation, quantity fluctuations, and schedule instability.

4. Application of 3D Visualization Intelligent System in Geotechnical Engineering Investigation and Design

4.1 System Architecture and Key Technologies

The system architecture adopts a layered design: "Data Base→Model Engine→Business Application→Visualization & Interaction." The Data Base core consists of unified coordinates and coding, ingesting multi-source information such as borehole logs, geophysical results, test data, monitoring, and construction logs. Built-in version and metadata management ensure traceability and temporal consistency. The Model Engine includes 3D stratum reconstruction, parameter field interpolation, transient groundwater simulation, and voxelization of engineering elements, supporting adaptive meshing and multi-scale processing to provide a computable carrier for subsequent analysis. At the Business Application level, functions like automatic quantity extraction, scenario simulation, clash detection, and threshold warning are integrated, providing toolkits for investigation layout optimization, scheme comparison, and construction organization review. Visualization & Interaction employs lightweight 3D rendering and multi-terminal adaptation, supporting sectioning, measurement, timeline playback, and result comparison, facilitating cross-disciplinary communication. Key technologies encompass heterogeneous data fusion, coordinate datum unification, parameter uncertainty expression, bidirectional model-monitoring association, and logged computational workflows, building a closed-loop chain from data ingestion to result publication, enhancing the accuracy and verifiability of geotechnical engineering investigation and design.

4.2 Data Acquisition and Multi-Source Fusion

Data acquisition and multi-source fusion emphasize ensuring usability and consistency from the source. The system establishes collection standards and quality control rules for channels like borehole logging, sampling tests, geophysical results, surveying, and monitoring, preserving original records, coordinates, and timestamps. After format parsing and unit verification via data gateways, thematic databases are built for strata, structures, groundwater, and engineering elements, recording acquisition conditions and instrument accuracy. The fusion process employs spatial matching and scale conversion to align profiles, discrete points, and raster data to a unified reference frame. Appropriate interpolation and zonal statistics are used to generate parameter fields, while simultaneously annotating confidence intervals and data coverage[5]. For external data like existing utilities, foundations, and surrounding buildings, participation levels are controlled through ownership and accuracy tags to avoid erroneous mixing. Dynamic monitoring and construction data are periodically ingested, establishing bidirectional links with model elements, enabling time series to be located to specific positions and working conditions within the 3D scene, providing a reliable data foundation for subsequent analysis and comparison.

4.3 Geological Model Construction and Analysis

Geological model construction and analysis premise on the spatial consistency of multi-source evidence. First, interface control points are determined based on borehole strata, geophysical anomalies, and surface surveys. Then, strata bodies are reconstructed using surface constraints and fault geometry rules. Weak interlayers, lenses, and fill areas are modeled separately to avoid homogenization. During parameter assignment, lab/field test results, in-situ tests, and monitoring inversion results are mapped to grids and voxels, distinguishing engineering geological units and statistical zones to form continuous fields for strength, deformation, permeability, etc., with smoothing and annotation applied to boundary transition zones. Analysis functions focus on excavation disturbance, dewatering effects, and load paths, supporting sectioning, isosurface generation, and volume measurement, quickly generating risk concentration areas combined with load cases. For groundwater systems, transient response calculations utilize aquifer connectivity and recharge/discharge conditions, enabling deformation and displacement predictions to be traced back to specific strata and parameter sources, serving investigation optimization and design comparison.

4.4 Construction Process Simulation and Monitoring

Construction process simulation and monitoring use "process + time" as the main thread. Excavation, support, dewatering, backfilling, and other steps are scheduled by day or week and played back step-by-step in the 3D interface, concurrently updating soil deformation and water level changes. Field construction logs, equipment operation information, and monitoring point readings are automatically ingested by time and associated with corresponding locations, facilitating plan vs. actual comparison. Components like support piles, capping beams, and struts record installation time, elevation, and pre-stress; the system generates lists, and abnormal readings are flagged in the model. Dewelling well activation/deactivation, rainfall events, etc., are added as time-varying boundaries, allowing visualization of the impact of water level drawdown and recovery on surrounding structures and utilities. If the construction pace adjusts or site conditions change, simply modifying the schedule or parameters quickly generates new progress scenarios. Risks at key locations and process sequencing can be intuitively seen through sectioning, measurement, and comparison views, facilitating communication and record-keeping.

5. Conclusion

In summary, throughout the entire process from engineering investigation to design and construction, the 3D visualization intelligent system is not merely a presentation tool but a working platform integral to data management, model computation, and collaborative decision-making. Through a unified data base, traceable parameter system, and computable spatial model, investigation understanding can be continuously updated, design assumptions can be validated, and construction processes can be quantitatively compared. Multi-source information converges within the same spatio-temporal framework, forming a closed-loop among geological bodies, engineering elements, and monitoring feedback, exposing risk clues earlier and clarifying impact ranges. This system enhances the transparency and verifiability of geotechnical engineering decisions, providing stable support for scheme comparison, schedule organization, and safety control in complex scenarios, possessing promotable technical value and application prospects.

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