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

The development of urban space will be deeper and denser, deep excavation, ultra-long tunnel, complex stratum construction are ascendant. Traditional point boreholes and the two-dimensional (2D) profile-based methods typically fail to adequately represent heterogeneity, as well as structures that vary continuously. There are often also information discontinuities between investigation, design and construction. As a result, schedule and cost deviations, delayed risk identification, insufficient cross-disciplinary collaboration have gradually becoming the key limitations to project quality and safety. By providing spatio-temporally integrated data as a carrier, 3D visualization intelligent systems couple multi-source observations, test results and engineering parameters together to directly demonstrate subsurface media with uncertainty. This also supports scheme comparison, change management and enables monitoring feedback loops. This need and opportunity for geotechnical engineering to develop a system of investigation and design that is traceable, updates easily with new data, and can better predict subsurface conditions over long time spans. This paper is expected to propose a systematic application roadmap for engineering practice from system architecture, data fusion, geological model and parameter field representation, computational analysis, and link with construction simulation and monitoring perspective.

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 are usually set up by combining data associated with boreholes, geophysical exploration, tests and monitoring obtained during the investigation stage to one platform. By replacing the former scattered 2D drawings and textual descriptions with standardized, comprehensive and intuitive representations in 3D of geological bodies and key

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parameters for standardization [1]. The estimation of scheme comparison and sensitivity based on a unified model is helpful for finding unfavorable factors, such as weak interlayers, sudden change of strata, high water table earlier. This provides an intuitive basis for crucial decisions like support types, dewatering layouts or excavation sequences etc., minimizing deviations caused due to excessive conservatism or partial value selection. It is capable of expressing these uncertainties as ranges or scenarios, and updating them dynamically in conjunction with monitoring data to guarantee design assumptions correspond with field performance whilst deciding on optimal parameter selection and safety factor settings. In this way, justification evidence becomes explicit, communication costs are minimized, design decisions more traceable and verifiable: all of which contribute to a better understanding of the completeness of investigation at hand as well as providing reliability for design conclusions. It is appropriate for a daily use and dissemination in many types of geotechnical civil engineering problems.

2.2 Building Data Closed-Loops and Collaborative Mechanisms

Without bridging data from various stages onto a common platform, it is difficult to enable ongoing engineering decision analysis. From hereon, 3D visualization intelligent systems set unified standards as well as coordinating frameworks and continuously aggregate data from investigation to design, construction to operation and maintenance forms a closed-loop in the form of "collection → modeling → analysis → feedback → re-optimization". Spatial-temporal data matching of boreholes, geophysical surveys, lab/field tests, monitoring points and construction log Finally, all parameter changes are instantaneously highlighted in the model and recorded with an associated version history, giving clear justification for a particular change and who is responsible. During the design process, calculations of loads, seepage and deformation are compared with field monitoring curves, and any deviations from limits result in warnings that lead to support optimisation or changes to construction speed. This, in turn, results in a transferable knowledge base as revised parameters then modify the database itself. Compared with the previous cross-disciplinary cooperation among disciplines, geotechnical, structural and MEP professionals can find problems and check conflicts in the same 3D environment which reduces information distortion and repeat modeling [2].

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

For 3D visualization intelligent systems, cost and risk management in the investigation and scheme demonstration stages is front-loaded. Using borehole, geophysical and test results data in a 3D integrated manner helps to find weak zones, water inflow lanes and sensitive structures affecting areas. This enables cost-efficient optimization of the support levels, dewatering/drainage layouts, and excavation sequencing minimizing design changes and rework. Based on the unified model, automatic quantity take-off and parametric comparison are carried out to quantify material consumption, critical path and equipment usage, which can be used to verify budget design basis for procurement decisions. Key MCC (Modular Construction Constriction) processes and site logistics are simulated prior to construction, impact windows on adjacent structures and utilities are clarified in terms of time duration, alarm thresholds are set, monitoring sections are established, and an early warning → response→ review mechanism is created. In the process of construction, the monitoring data is fed into the model back and helps in dynamically correcting parameter specification and boundary conditions to avoid redundant investment by putting excessive safety margins while keeping effective risk control.

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

3.1 Dispersed Information

The aspects of data dispersion are mainly manifested in multiple sources, different formats, inconsistent catch-up times and semantic mismatch. Different units and personnel produces the exploration boreholes, geophysical profiles, sampling and testing, Monitoring records and Construction logs. Fluctuating coordinate datums, coding systems and standards of accuracy result in divergent records as well as repeated descriptions of identical stratum or parameter across outside sources [3]. The 2D drawings and text reports have no machine-readable links between those two modalities, making it impossible to establish direct correspondence from a spatial location in the drawing to a specific time point of an event, leading to "point evidence" having disjointedness. Because weak version management renders adjustments in the past untraceable and revisions are typically made with no know-how of the ensembles state. With abstraction and a focus on summarisation in between stages, entries can exist in that they cannot be counted or presented as physical units. Moreover, dynamic information that is produced as a result of monitoring and construction challenges the ability to feed it into the investigation understanding system within appropriate timescales leading to a disconnect between design basis and field.

3.2 Inadequate 3D Representation

3D geoscience data are still largely limited in format to 2D profiles, single-borehole logs and discrete measurement points; results are often difficult to reconcile with the true morphology of undulating stratum interfaces, as well as planar or curved but continuous weak interlayers and fracture structures. Unfortunately, local extrapolation leads to oversimplification or unreasonable splicing. The abundance of different coordinate systems and scaling used for most geophysical and test results prevents the proper alignment in 3D space hence, volumetric models are often left as just a 'tape measures'. Geotechnical parameters are presented in the forms of tables or zonal averages, which is not easily linked with spatial grids and since parameters such as permeability coefficients, stiffness indices and strength indices cannot create continuous fields to provide domain boundaries and loading descriptions for subsequent analysis. Static surface characteristics primarily depict the temporal patterns of groundwater levels and aquifer structures, failing to capture dynamic responses under seasonal influences or construction disturbances. The spatial position of utilities, foundations, and existing structures is often either unavailable or inadequate to determine the risk of conflict between engineering elements and geological bodies in a 3D context.

3.3 Difficulties in Cross-Disciplinary Collaboration

The omnipresence of unclear information boundaries and inadequate model interoperability centrally manifests crossdisciplinary collaboration challenges. As an example, geotechnical, structural, plumbing, MEP or transportation disciplines each use their own software and its own coding system. Because interface conditions often need to be revalidated with inconsistent data formats, coordinate datums, and naming conventions, it comes as no great surprise that seamless model integration is a challenge. Professional outputs are only static drawings (drawn but not spatial data or parameter descriptions) a drawing generated which needs direct work after submitted. Review comments and modification records are present across emails and attachments, making the source of each version hard to verify. Clash detection and impact analysis usually happen quite late in the process, initial assumptions are often inconsistent and a range of design iterations can impact the schedule. Field changes, monitoring information, and design model all update at different paces; some disciplines run off old information and this hurts decision-making.

3.4 Uncertainty Propagation and Amplification

Sources of uncertainty propagation and amplification are predominantly via data source stacking, parameter selection, or model assumptions. The large spatial extrapolations involving stratum interfaces and weak interlayers are particularly poorly constrained by sparse, pointwise investigation. Sampling disturbance and different testing methods that do not give stable centroids in the distribution of test indices. Such uncertainties are embedded and propagated through the mesh generation process, boundary specification, and load input processes in the 3D model. Coupled errors are difficult to track back due to inconsistent value selection criteria on the part of different disciplines (for example, seepage problems, strength reduction effects and load case combinations) [4]. Short term deviations from the truth are also due to that construction disturbances and groundwater temporal variations do not readily reflect into too many days, and there are delays or missing monitoring data which adds complex mechanisms of prediction error. Overshadowed version updates, and lack of metadata allow parameter use to become self-replicating local conservatism or radicalism through the credit assignment of multiple steps; this ultimately leads to systematic bias as descending into imbalanced safety margin allocation which can lead to variance blowing up and schedule instability.

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

4.1 System Architecture and Key Technologies

In The Layered Architecture of system: Data Base→Model Engine→business Application→Visualization & Interaction. Unified coordinates and coding in the Data Base core, all information, whether borehole logs, geophysical results or test data, monitoring or construction log are ingested from multi-sources. Traceability, temporal consistency is ensured by built-in version and sidecar for metadata. The Model Engine is capable of 3D stratum reconstruction, parameter field interpolation, transient groundwater simulation, and voxelization of engineering elements with functions such as adaptive meshing and multi-scale processing that provide a computable carrier for follow-up analysis. Concurrently, functions such as automatic quantity extraction simulation of construction scenarios, identification of clashes among elements, and warning about deviations beyond threshold parameters are integrated at the Business Application level. Visualization & Interaction utilizes lightweight 3D rasterization and has a multi-terminal adaption by means of sectioning, measurements, playback on the timeline and contrasting of results to promote cross-region communication. Key technologies involve heterogeneous data fusion, coordinate datum unification, parameter uncertainty expression, bidirectional model-monitoring associations and computational workflows logged building a closed-loop chain from data ingestion to result publication that greatly improves the confidence and verifiability of geotechnical engineering investigation and design.

4.2 Data Acquisition and Multi-Source Fusion

The emphasis of data acquisition and multi-source fusion is to ensure usability and consistency from the source. It sets rules to collect deviations and standards and QC protocols for channels e.g. borehole logging, sampling tests, geophysical results, surveying & monitoring among others; keeps original records of these; ropes in timestamps/coordinates etc. Data gateways are then used for parsing the format and verifying the unit of elements, and thematic databases are built separately to account strata, structure, groundwater, and engineering components capturing acquisition conditions as well as instrument accuracy. Fusion combines profiles, discrete points and raster data to a common reference through spatial matching and scale conversion. Parameter fields are produced by appropriate interpolation and zonal statistics while confidence intervals and data coverage are interpolated simultaneously [5]. Finally, for the external data sets, such as existing utilities, foundations and surrounding buildings, participation levels are restricted with ownership and accuracy tags to prevent inadvertent mixing. Dynamic monitoring and construction data should be routinely integrated, with bidirectional mapping to model elements as well so that time series can be assigned to certain positions and working conditions in the 3D scene; thus supporting a reliable foundation for further analysis and comparisons.

4.3 Geological Model Construction and Analysis

Building and analyzing geological models rely on the spatial coherence of information from multiple sources. First, from borehole strata and geophysical anomalies, as well as topographic surface surveys, interface control points are determined. Lastly, using surface constraints and fault geometry rules, strata bodies are reconstructed. Homogenization is avoided by separately modeling weak interlayers, lenses, and fill areas. During the parameter assignment process, lab/field test results, in-situ tests, and monitoring inversion results are mapped to grids/voxels distinguishing engineering geological units/statistical zones into continuous fields of e.g. strength/deformation/permeability/etc with smoothing or annotation for boundary transition zones (e.g. Domain reduction for excavation disturbance, dewatering effects and load paths supporting sectioning, isosurface generation, volume measurement: fast analysis function to generate risk concentration areas with existing combination of loading cases. Analytical approximations that use knowledge of aquifer connectivity and recharge/discharge conditions in the calculations for groundwater systems provide elastic response estimates, making it possible to backtrack deformation and displacement predictions to specific strata and parameter sources useful for optimizing investigations or comparing designs.

4.4 Construction Process Simulation and Monitoring

The two core elements of the construction process simulation and monitoring are "process + time". This involves day or weekly schedules for excavation, support, dewatering, backfilling and other steps being played one at a time in the 3D interface while soil deformation and water level changes concurrently take place. Time-stamped field construction logs, equipment operation details, and those readings from monitoring points are automatically ingested and linked to the right locations for plan vs. actual comparisons. Support piles, capping beams and struts capture installation time, elevation and pre-stress; List from system GES (global engineering service) Abnormal readings are flagged in the model. Time varying boundaries which include dewelling well activation/deactivation, rainfall events etc., are added and allow users to visualize the impact of drawdown/recovery in water levels in surrounding structures and utilities as well. In the event the construction pace is put on hold or the site conditions adapt you can amend the schedule/parameters at a flick of a switch to see scenarios for how progress alters. Sectioning, measurement and comparison views of data from the key places in process sequencing allow users to intuitively visualize risks that must then be recorded and communicated.

5. Conclusion

The entire 3D visualization intelligent system is not just a presentation tool in all process from engineering investigation through design to construction, but also the working platform involving data management, model computation and collaborative decision-making. A unified data base, a traceable parameter system, and an explicit spatial model allow for the continual updating of investigation understanding, the validation of design assumptions and the quantitative comparison of construction processes. Required multi-source information also converges in the same spatio-temporal framework to form a closed-loop among geological bodies, engineering elements and monitoring feedbacks, which reveal threat clues ahead of time and details impact ranges. The system can increase the transparency and verify-ability of decision making in geotechnical engineering with stable support for scheme comparison, schedule organization, and safety control under complex conditions, which has promotable technical value and application prospect.

References

[1] Li X.H., Chang R.L., Han B. Application of 3D Visualization Intelligent System in Geotechnical Engineering Investigation and Design [J]. Petroleum & Chemical Construction, 2024, 46(2): 50-53.

[2] Hou J.F. Application of BIM Technology in 3D Visualization of Geotechnical Investigation Results [J]. Brick and Tile World, 2023(6): 22-24.

[3] Wang Q., Xie L.W., Jiang J., et al. Preliminary Research on 3D Visualization of Geotechnical Investigation Results Based on BIM Modeling [J]. Urban Geotechnical Investigation & Surveying, 2021(5): 206-208.

[4] Wang S.L. Effective Application of BIM in 3D Visualization of Geotechnical Investigation Results [J]. Zhongzhou Construction, 2021(6): 32-33.

[5] Zhou X.L. Research on the Application of BIM in 3D Visualization of Geotechnical Investigation Results [J]. Building Technique Development, 2020, 47(7): 158-159.