Discussion on Geotechnical Engineering Design Technology Based on Risk Control

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Abstract: Geotechnical engineering is a foundational field in the construction industry, and its design quality is closely related to the safety and stability of the entire project. The geological conditions of geotechnical engineering are complex, and factors such as groundwater level fluctuations and geological hazards pose significant challenges to its design. Traditional design methods are often ineffective in dealing with such complex risks. This paper analyzes the advantages of risk control-based geotechnical engineering design, proposes key design technologies and optimization strategies—such as identifying dynamic risks through geological surveys, optimizing limit state design, improving construction techniques, formulating multi-dimensional risk transfer mechanisms, and implementing full lifecycle monitoring—to provide a robust reference for the successful construction of geotechnical engineering projects.

1. Introduction

The design quality of geotechnical engineering is closely tied to the safety and stability of the entire engineering project. Reasonable geotechnical engineering design must meet regulatory requirements and basic functional needs. As the scale of geotechnical engineering continues to expand and technical requirements become stricter, accurately identifying and controlling risks has become an urgent issue for construction units. Therefore, risk control-based geotechnical engineering design must integrate risk management thinking into all processes, use modern methods to systematically classify and quantitatively assess risks, and develop scientific and reasonable emergency measures and design schemes to provide practical guidance for steadily improving the level of geotechnical engineering design.

2. Advantages of Risk Control-Based Geotechnical Engineering Design

2.1 Enhancing the Scientific Nature of Design Decisions

Risk control-based geotechnical engineering design provides strong data support for engineering design decisions through systematic identification and quantitative analysis. Risk control requires multi-dimensional modeling of geological conditions and material properties, combined with probabilistic statistical methods to assess uncertain factors. Additionally, risk assessment enables real-time updates of geological survey data and environmental change parameters during the design of foundation pit support, helping to control project costs while ensuring construction safety.

2.2 Strengthening Engineering Adaptability

Geotechnical engineering under a risk control framework enhances adaptability by accurately identifying risk factors such as geological uncertainties and construction interferences. Based on quantitative analysis, a risk level matrix can be established. Furthermore, adaptive design leverages the advantages of modular structures to enhance the compatibility of geotechnical engineering with complex geological conditions, ensuring structural stability during both construction and operation

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phases.

2.3 Ensuring Full Lifecycle Safety of the Project

Risk control-based geotechnical engineering design systematically improves the safety of engineering projects throughout their lifecycle. During the design phase, potential safety hazards are identified through risk quantification analysis and geological survey data modeling, enabling the development of scientifically sound support structure selections and slope stability control schemes, thereby reducing the likelihood of engineering failures at the source. Additionally, full lifecycle risk control advocates for durability design in geotechnical engineering. With the support of high-quality anti-corrosion materials and drainage systems, long-term maintenance costs can be reduced. Moreover, the risk control system integrates data from various stages such as design, construction, and operation, providing a reasonable reference paradigm for the sustainable and stable development of geotechnical engineering.

3.Risk Control-Based Geotechnical Engineering Design Technologies

3.1 Multi-Source Information Fusion for Risk Identification

A core method in risk control-based geotechnical engineering design is multi-source information fusion for risk identification. This technology integrates multi-dimensional data from geological surveys, field monitoring, and numerical simulations to establish a comprehensive dynamic risk assessment system, enabling early warning and identification of risks throughout the entire lifecycle of a geotechnical engineering project [1]. Relying on geological survey techniques, it acquires information such as stratum conditions and geotechnical parameters. Combined with GIS platforms, it can create 3D geological models, providing a reliable spatial benchmark for risk identification. Furthermore, through coupled analysis combining real-time monitoring data and numerical simulations, this technology can quantify the disturbance impact of geotechnical activities on rock and soil masses, identifying potential risks. The application of IoT sensor networks enables synchronous collection of multiple parameters and edge computing. Coupled with cloud computing platforms, efficient big data fusion analysis can be conducted to dynamically revise risk model parameters, improving the timeliness of risk identification. This technology breaks the limitations of single information sources, reducing uncertain risk factors through information complementarity and cross-validation, providing a reliable reference for geotechnical engineering design.

3.2 Risk Transfer Design Technology

Risk transfer design technology in geotechnical engineering offers significant strategic advantages. It primarily uses mechanisms such as contracts and insurance to transfer difficult-to-control risks to other entities. At the contract level, the geotechnical engineering design team clarifies responsibility boundaries with multiple parties, including contractors and suppliers. For foundation construction in areas with complex geological conditions, the contract explicitly stipulates responsibilities for losses and repairs caused by improper contractor operations. Insurance mechanisms are also effective risk transfer measures. For natural disasters faced by geotechnical engineering, the design requires corresponding property insurance and all-risk insurance. In the event of a disaster, the insurance company will bear most of the economic losses according to the contract, thereby alleviating the financial pressure on the constructor. Additionally, risk transfer design technology can assign specialized, high-risk tasks to professional teams, transferring risks to subcontractors through contractual agreements, providing safeguards for the entire lifecycle of the geotechnical engineering project.

3.3 Parameter Dynamic Correction Technology

Parameter dynamic correction technology in risk control-based geotechnical engineering design provides a solid risk defense line through real-time and precise parameter adjustments. The geological environment of geotechnical engineering is fraught with variability, and the initial parameters used in design are often based on survey data and empirical assumptions. As the project progresses, these initial parameters may deviate from the actual conditions. Therefore, construction personnel should employ parameter dynamic correction technology, which uses real-time monitoring and data analysis to provide a scientific basis for precise parameter adjustments. Various high-precision sensors should be deployed on-site to keenly perceive changes in key indicators such as stress, strain, and displacement of the rock and soil mass. This massive data is continuously transmitted to a data processing center. Through analysis by advanced algorithmic models, parameter deviations can be accurately identified. If a parameter deviation exceeds the safety threshold, the system immediately issues an alert and automatically initiates a correction procedure. Construction enterprises use the updated parameters to reassess the safety status and risk level of the geotechnical engineering project. If the risk remains within an acceptable range, construction continues as planned; if monitoring data indicates that the risk exceeds expectations, an early warning must be issued to keep the risk always within the expected target threshold.

4 Optimization Strategies for Risk Control-Based Geotechnical Engineering Design

4.1 Utilizing Geological Surveys to Identify Dynamic Risks

Optimization of risk control-based geotechnical engineering design should treat geological surveys as the core means for dynamic risk identification. A multi-stage, multi-technology integrated survey strategy should be adopted to establish a closed-loop management system incorporating survey, feedback, and adjustment elements, achieving proactive risk management [2]. In the preliminary design stage, regional geological surveys and remote sensing interpretation should form the basis, combined with historical engineering data analysis, to identify macro geological risk zones such as fault fracture zones and weak interlayers, delineating high-risk boundaries. In the detailed design stage, a drilling plan combining grid and focused densification should be implemented. In risk-sensitive areas, double-tube single-acting core sampling technology should be used, coupled with standard penetration tests and dynamic penetration methods to obtain in-situ mechanical parameters. For special geological bodies, borehole television imaging and acoustic logging technologies should be introduced to enhance the accuracy of 3D geological modeling. Furthermore, geological exploration should incorporate probabilistic statistics and artificial intelligence analysis tools. GIS and BIM technologies should be used for 3D geological modeling to visually display the spatial distribution of geological bodies and their uncertainties. Survey personnel should further use machine learning algorithms to analyze parameter variability and model uncertainty, identifying key parameters and areas most sensitive to engineering safety, and concentrating limited survey resources on the highest-risk sections.

4.2 Optimizing Limit State Design

Limit state design in risk control-based geotechnical engineering should adopt multi-dimensional strategies to achieve a dynamic balance between safety, economy, and feasibility. Firstly, for key parameters such as soil shear strength and compression modulus, the Bayesian update method should be selected to integrate field test data and historical engineering experience, dynamically adjusting the design parameter distribution model to avoid resource waste caused by conservative design. Secondly, the traditional single limit state equation should be decomposed into a two-tier system of ultimate limit state (ULS) and serviceability limit state (SLS). A parameter sensitivity matrix should be established through finite element numerical simulation to identify dominant parameters with influence coefficients >0.3 for targeted optimization. On this basis, limit state design should be optimized for full lifecycle cost-oriented parameters, establishing an LCC (Life Cycle Cost) model including initial construction cost, operation and maintenance cost, and risk loss cost. Multi-objective optimization should be performed using genetic algorithms. For example, in geotechnical engineering slope support construction, the combination of anchor cable length and spacing can be adjusted to effectively shorten the construction period. Finally, the optimization strategy should run through the entire process of survey, design, construction, and operation. Flexible schemes should be designed using the observational method or value engineering concept. By monitoring data in real-time during construction, the risk level can be dynamically assessed [3]. Once monitoring values approach the warning threshold, preset reinforcement or adjustment plans should be activated immediately to achieve proactive risk control and dynamic design optimization, ultimately finding the optimal balance between cost and risk.

4.3 Reasonably Optimizing Construction Techniques

Optimization of construction techniques under the risk control framework should adopt multi-dimensional strategies to balance efficiency and safety. Construction enterprises should conduct refined stratification based on geological survey data, establishing a dynamic correlation model between construction parameters and stratum characteristics. In soft soil areas, layered and segmented excavation combined with graded support technology should be selected. The dewatering rate should be adjusted based on real-time monitoring of pore water pressure changes to avoid risks of quicksand or piping caused by over-excavation. For karst development areas, traditional bored piles should be optimized into composite support structures: the upper part uses rotary drilling cast-in-place piles to resist earth pressure, while the lower part embeds steel sleeves to traverse cavities, combined with advanced ground-penetrating radar scanning for accurate avoidance, controlling construction disturbance within the safe bearing capacity range of the stratum. Furthermore, construction enterprises can use BIM + digital twin technology to build 3D construction models for spatiotemporal conflict detection of processes such as support structure installation, earth excavation, and dewatering operations. During the process selection stage, a comprehensive comparative analysis of construction methods, risks, and costs is needed. Priority should be given to mature, low-disturbance techniques. Detailed special construction plans and emergency plans should be prepared and fully communicated. It is also crucial to strictly control material quality, equipment performance, and construction operational procedures, ensuring every process meets design and technical standards.

4.4 Formulating Multi-Dimensional Risk Transfer Mechanisms

Optimization of risk control-based geotechnical engineering design should build multi-dimensional risk transfer mechanisms, leveraging the synergistic advantages of technical, contractual, financial, and management means to achieve rationality and dynamic balance in risk allocation. Construction enterprises should establish a geotechnical engineering risk database referencing geological survey data and numerical simulation technology, conducting probabilistic analysis of typical risks such as landslides, settlement, and seepage. On this basis, replaceable standardized components should be used to reduce systemic risks caused by single component failures. Construction enterprises should include foreseeable risks, such as geological uncertainty, within the contractor's responsibility scope, achieving risk premium compensation through adjusted contract pricing mechanisms. For extreme risks that could cause significant financial losses, purchasing professional engineering insurance is essential. For particularly large projects, exploring risk securitization through capital markets or cooperation with insurance companies can further disperse accumulated catastrophic risks, ensuring ultimate financial stability for the project.

4.5 Implementing Full Lifecycle Monitoring

Optimization of risk control-based geotechnical engineering design requires the implementation of full lifecycle monitoring. A 3D geological model and risk database should be established, integrating technologies such as sensor networks, satellite remote sensing, and UAV inspections. Key deployment of intelligent optical fiber sensors, distributed strain gauges, and other equipment is necessary to real-time collect key parameters like displacement, stress, and seepage, forming a multi-dimensional monitoring matrix [4]. On this basis, construction enterprises should adjust risk thresholds in phases. During the construction phase, warning thresholds for deformation rate and support structure stress under various working conditions should be set based on numerical simulations. Furthermore, the construction of geotechnical engineering projects should establish a digital twin platform combining BIM and GIS, integrating real-time monitoring data and finite element analysis modules. Post-project delivery monitoring strategies should transition to long-term operation, maintenance, and health diagnosis. Permanent monitoring sensors should be used to continuously track the long-term performance evolution of the rock/soil mass and structures. Scientific prediction models should be established through long-term data analysis to support future maintenance decisions, maximizing the value of the asset throughout its lifecycle.

5. Conclusion

In summary, risk control in the field of geotechnical engineering is a fundamental condition for ensuring project safety. With the continuous emergence of new technologies and ideas, geotechnical engineering must also optimize its design from the perspective of risk control. By utilizing geological surveys for dynamic risk identification, optimizing limit state design, reasonably improving construction techniques, formulating multi-dimensional risk transfer mechanisms, and implementing full lifecycle monitoring, a foundation is provided for the high-quality development of geotechnical engineering.

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