Application Analysis of Geotechnical Engineering Survey Technology under Complex Geological Conditions

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Abstract: This study addresses the challenges of technical adaptation difficulties and low data accuracy in geotechnical engineering surveys under complex geological conditions. Based on a multi-technology collaboration and process optimization approach, it analyzes the complete application process of geotechnical engineering survey technology in such scenarios. The study summarizes the operational logic of four core stages: preliminary geological prediction, multi-technology field data collection, data processing and modeling, and result validation. Additionally, it elaborates on three optimization approaches: introducing intelligent equipment, establishing a cross-technology data-sharing platform, and conducting targeted technical adaptability tests. Through systematic and practical verification, the proposed application process effectively mitigates interference from complex geological conditions, enhancing data integrity and reliability. The optimization approaches further reduce survey errors and improve operational efficiency, providing a practical technical framework for geotechnical engineering surveys under complex geological conditions. This framework also lays a data foundation for the safe advancement of subsequent engineering designs, addressing the core issue of inadequate adaptability of traditional survey technologies in complex geological settings.

1. Introduction

Currently, China's infrastructure construction is continuously expanding into deep and remote areas, leading to an increasing number of complex geological scenarios such as karst development zones, fault fracture zones, and alternating layers of soft soil and hard rock. These geological conditions are characterized by complex stratigraphic structures and high uncertainty, often causing survey issues like borehole wall collapse and data distortion. Traditional survey methods, which rely heavily on single drilling techniques, struggle to comprehensively capture complex geological information, resulting in deviations between survey data and actual geological conditions. This, in turn, affects the rationality of engineering designs, increases construction safety risks, and raises cost inputs. Against this backdrop, systematically organizing the application process of geotechnical engineering surveys under complex geological conditions and exploring optimization approaches to enhance survey effectiveness have become crucial for addressing current survey challenges and ensuring safe engineering construction. This paper will analyze the application process and optimization approaches, providing technical references for geotechnical engineering surveys in complex geological scenarios.

2. Application Process of Geotechnical Engineering Survey Technology under Complex Geological Conditions

2.1 Preliminary Geological Condition Prediction and Scheme Design

Multi-source Geological Data Collection and Integrated Analysis: First, obtain regional 1:50,000 geological maps, previous engineering survey reports, and borehole data from local geological survey institutes. Focus on marking the approximate distribution ranges of complex geological bodies such as faults, karst caves, and weak interlayers. Then, utilize high-resolution remote sensing

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images with a resolution of no less than 0.5 m to identify surface cracks and abnormal topographic areas through image interpretation, preliminarily judging the extension trends of underground geological structures [1]. Cross-validate the collected data by comparing the stratigraphic lithology revealed by boreholes with the surface features interpreted from remote sensing images. If contradictions exist, mark the questionable areas for focused attention during subsequent surveys. Determination of Survey Boundaries Based on Engineering Types: Generally, extend the engineering influence range by 50–100 m to define the survey scope. Select appropriate technologies based on different complex geological characteristics: In karst development zones, in addition to conventional drilling, employ geological radar detection with a detection frequency of 25–100 MHz to ensure penetration of 10–30 m of strata for karst cave identification. In fault fracture zones, densify borehole layouts with a hole spacing reduced to 10–20 m, and ensure that boreholes penetrate the fault zone and enter stable strata by no less than 5 m to obtain complete fault mechanical parameters [2].

Risk Disposal Procedures: Clearly define disposal procedures for potential risks during surveys, such as water inrush, borehole collapse, and harmful gas overflow. For water inrush, immediately stop drilling, insert a water-stop casing, and activate pumping equipment while recording water inflow and pressure data. For borehole collapse, adopt casing-following drilling or inject 护壁 (wall-protecting) mud with a specific gravity controlled between 1.2 and 1.4. Quality Control Indicators for Surveys: Ensure that the verticality deviation of boreholes does not exceed 1% and the data collection rate of geological radar is no less than 95% to guarantee the standardization and safety of scheme implementation.

2.2 Multi-technology Collaborative Field Data Collection

Drilling Technology in Complex Strata: In complex strata such as alternating layers of soft soil and hard rock and weathered rock layers, adopt casing-following drilling techniques with casing diameters ranging from 108 to 146 mm. The casing should be lowered to a depth exceeding the unstable strata by 3–5 m. Adjust the drilling speed dynamically based on stratigraphic lithology: control the speed at 0.8–1.2 m/min in soft soil layers and reduce it to 0.3–0.5 m/min in hard rock layers to avoid rock core breakage due to excessive drilling speed. Rock Core Collection and Description: Limit each round-trip drilling advance to no more than 2 m and ensure a rock core recovery rate of at least 85% (no less than 65% in broken strata). Number, photograph, and describe the rock cores, focusing on recording features such as the degree of fracture development and cementation status to provide a basis for subsequent stratigraphic classification [3]. Concurrent Geophysical Exploration: During drilling operations, conduct geophysical exploration concurrently. For high-density electrical methods, use the Wenner array with an electrode spacing of 5–10 m, matching the measurement depth with the drilling depth to identify underground karst caves and water body distributions through resistivity differences. For seismic refraction methods, employ a hammer blow source with a geophone spacing of 3–5 m, recording seismic wave propagation times to calculate stratigraphic wave velocities and determine stratigraphic interfaces. Compare and analyze the two sets of geophysical data. If the low-resistivity anomaly area identified by high-density electrical methods aligns with the low-velocity layer identified by seismic refraction methods, it can be preliminarily judged as a karst cave or water-bearing layer, requiring focused verification by subsequent drilling.

In-situ Testing: Immediately conduct in-situ tests after completing drilling holes. For standard penetration tests, maintain stable hammer blow energy with a 63.5 kg hammer and a free-fall distance of 76 cm, recording the number of blows for every 30 cm penetration. Conduct tests every 1–2 m within the same borehole. For pressure water tests, adopt the single-point method with a test pressure set at 1.2 times the engineering design water head. Stabilize each pressure level for 30 min and record the water pressure volume to calculate the rock mass permeability coefficient. Correlate in-situ test data with drilling rock core characteristics. For soft soil layers, the standard penetration blow count is usually less than 5. If an abnormally high value occurs, check whether the testing equipment is functioning properly or if there are interlayers in the strata [4]. Real-time Data

Collection and Verification: Equip portable data collection terminals to record drilling, geophysical exploration, and in-situ test data in real-time into the system. After completing each survey point, verify on-site whether the drilling advance, geophysical curves, and test readings are complete. If data is missing or abnormal, immediately recollect it to avoid difficulties in later data supplementation.

2.3 Data Processing and Geological Model Construction

Data Preprocessing: For drilling data, exclude abnormal round trips with a rock core recovery rate below 60% due to borehole wall collapse and supplement the data with interpolation from adjacent boreholes. For geophysical data, use professional software such as RES2DINV for high-density electrical method data processing and SUFER for seismic refraction method data processing to filter out noise caused by electromagnetic interference and topographic effects. Smooth the geophysical inversion results to reduce boundary effect errors. For in-situ test data, make corrections such as adjusting standard penetration test results based on groundwater level and stratigraphic density and converting pressure water test data to permeability coefficients under standard conditions to ensure comparability of data from different survey points [5]. Calculation of Geotechnical Parameters: Calculate key geotechnical parameters from the preprocessed data. Use the weighted average method to calculate the natural unit weight of strata based on layer thickness weighting. Fit Mohr-Coulomb strength parameters through shear strength test data. Conduct statistical analysis on parameters within the same stratum to calculate the mean, standard deviation, and coefficient of variation. If the coefficient of variation exceeds 0.3, analyze the abnormal causes, such as fault influence, and supplement test data. Organize the parameters by stratum to form a parameter table, indicating the sample size and confidence level for each parameter to provide reliable inputs for model construction. Geological Model Construction: Select software such as GeoStudio or FLAC3D to construct the model. First, import topographic data to build the surface model. Then, based on stratigraphic interfaces revealed by drilling and geological structures identified by geophysical exploration, construct stratigraphic models layer by layer. For complex geological interfaces such as karst cave roofs and fault contact surfaces, adopt fine grid subdivision with a grid size controlled between 1 and 5 m to accurately reflect interface morphology. Assign calculated geotechnical parameters to each stratum and assign values separately to special areas such as fault zones and karst caves. After model construction, conduct topology checks to ensure reasonable stratigraphic contact relationships without suspended or overlapping areas [6]. Model Simulation and Analysis: Set up engineering scenarios such as foundation pit excavation and tunnel construction that may be encountered during construction. Simulate stress and displacement changes in geotechnical materials under different scenarios. For example, during foundation pit excavation simulation, apply unloading in layers according to excavation depth and calculate ground settlement and horizontal displacement around the foundation pit. During tunnel construction simulation, analyze the stability of surrounding rock during the advancement of the tunnel face. Extract simulation results from key areas such as the foundation pit bottom and tunnel arch top and compare them with engineering safety limits. If the limits are exceeded, mark the risk areas and propose optimization suggestions for subsequent designs to enable the model to provide quantitative support for engineering designs.

3. Approaches to Optimize the Application Effectiveness of Geotechnical Engineering Survey Technology

3.1 Introduction of Intelligent Monitoring Equipment to Improve Data Accuracy

Equipment Selection: Choose appropriate equipment based on the characteristics of complex geological conditions. In mountainous areas with significant topographic relief, select unmanned aerial vehicles (UAVs) equipped with high-definition optical cameras (resolution of at least 20 million pixels) and high-precision inertial measurement units. For areas requiring monitoring of micro-changes in deep strata, opt for fiber-optic sensors with micro-strain-level accuracy [7].

Installation and Debugging: Calibrate the positioning system of UAVs in open areas to ensure positioning accuracy within ±0.5 m. For fiber-optic sensors, clean the boreholes before installation to ensure smooth hole walls. Slowly lower the sensors along the borehole walls and fix special anchoring agents. Then, conduct wavelength calibration and signal testing to ensure stable signal transmission.

Data Collection and Analysis: UAVs should fly at a speed of 5–10 m/s along preset routes with an image collection frequency of 5–10 frames/s. Fiber-optic sensors should collect data at a frequency of once per minute. After preprocessing the collected data through filtering and noise reduction, use professional software for analysis to generate curves of topographic changes and stratigraphic stress-displacement changes, providing precise data support for surveys.

3.2 Establishment of a Cross-technology Data-sharing and Collaborative Platform

Platform Architecture Selection: Adopt a distributed architecture to ensure efficient and stable data storage and processing. The platform should include functional modules such as data entry, storage, query, analysis, and visualization. Data Access and Integration: Drilling data can be entered manually or automatically imported through instruments into the platform. Geophysical data should be converted to a compatible format before access. In-situ test data should be transmitted to the platform in real-time. Use data cleaning algorithms to remove abnormal data and data association algorithms to establish links between data from different technologies, such as associating the depth of geotechnical samples obtained from drilling with the stratigraphic interface depth determined by geophysical exploration [8].

Collaborative Operation Function Development: Set different user permissions to enable survey personnel to upload and update data in real-time and design personnel to query and analyze data online. The platform should support online discussions and feedback functions to facilitate communication between the two parties, ensuring smooth data flow from surveys to designs, improving data utilization efficiency, and reducing design deviations caused by information gaps.

3.3 Conducting Targeted Technical Adaptability Tests

Test Area Division Based on Geological Types: Set up 3–5 test points in high-altitude permafrost strata and 5–8 test points in coastal soft soil strata. Determination of Test Technologies and Indicators: In permafrost areas, test the effects of different drilling fluids on borehole stability and permafrost thawing, with indicators such as borehole collapse rate and permafrost thawing depth. In soft soil areas, compare the shear strength parameters obtained from static penetration tests and vane shear tests, with an indicator of parameter difference rate. Test Implementation: Conduct technical tests according to norms at each test point. During permafrost drilling, control the drilling speed at 2–3 m/h and record the effects of different drilling fluids. In soft soil areas, conduct the two types of tests at intervals of 1–2 m to ensure consistent test environments [9]. Data Analysis and Guideline Formation: Use statistical analysis methods to calculate indicators such as mean values and standard deviations from the test data. Compare the performance of different technologies and form technical application guidelines for specific geological conditions, providing standardized processes for subsequent surveys and enhancing the adaptability of technologies to complex geological conditions.

4. Conclusion

This study has clarified the core application system of geotechnical engineering survey techniques under complex geological conditions: By integrating multi-source geological data and conducting cross-validation, tailored survey plans and risk contingency plans are formulated in accordance with engineering requirements, thereby ensuring the safe and standardized implementation of surveys. The adoption of an integrated approach combining "drilling, geophysical exploration, and in-situ testing," along with the adjustment of technical parameters and operational methods for different complex strata, effectively enhances the completeness and accuracy of data. Through data preprocessing, parameter statistics, and refined modeling, discrete survey data can be transformed into visual and simulatable three-dimensional geological models, providing a quantitative analytical basis for engineering design.

The study found that the introduction of intelligent equipment can improve data collection accuracy, the establishment of a data-sharing platform can optimize data utilization efficiency, and the implementation of technical adaptability tests can enhance the technology's suitability for complex geological conditions. The synergistic application of these three aspects can significantly improve the overall performance of survey techniques, addressing issues such as significant data errors, poor information transmission, and low technical adaptability in traditional surveys.

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