Research on the Impact of Hydrogeological Conditions on Mine Geotechnical Engineering Design and Countermeasures

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Abstract: This study focuses on the safety and quality issues arising from hydrogeological conditions in mine geotechnical engineering design. Based on actual engineering scenarios, it analyzes the impact of groundwater pressure, corrosivity, and water level changes on design. It summarizes the current problems in design, such as insufficient monitoring, disjointed protection measures, and delayed predictions. Through specialized investigations, material and process optimization, and dynamic control methods, it elaborates on specific countermeasures, including accurately determining groundwater parameters, implementing targeted anti-corrosion measures, and dynamically monitoring and regulating water levels. The aim is to demonstrate that these countermeasures can effectively solve problems such as rock-soil mass instability, structural corrosion, and construction safety hazards, providing scientific support for mine geotechnical engineering design and enhancing engineering safety and durability.

1. Introduction

As mining operations advance deeper underground, the constraints imposed by hydrogeological conditions on geotechnical engineering design have become increasingly prominent. Fluctuations in groundwater pressure can easily cause slope sliding. Corrosive groundwater shortens the service life of structures, and sudden rises or falls in water levels pose threats to construction safety. If these issues are not properly addressed, they will increase engineering risks and costs. Currently, in design, the consideration of hydrogeological conditions often has limitations and is difficult to adapt to complex engineering requirements. Therefore, it is necessary to systematically sort out the impact mechanisms of hydrogeological conditions and propose targeted countermeasures to provide feasible paths for mine geotechnical engineering design.

2. Impact of Hydrogeological Conditions on Mine Geotechnical Engineering Design

2.1 Decline in Rock-Soil Mass Stability Due to Groundwater Pressure

In the context of groundwater pressure in current mine geotechnical engineering, there is insufficient emphasis on long-term dynamic monitoring of the head height of confined water. Most projects only conduct a limited number of head measurements during the initial investigation stage and fail to establish a real-time monitoring mechanism throughout the entire engineering lifecycle. As mining operations progress, changes in the stratum structure and the connectivity of aquifers can cause significant fluctuations in the head of confined water. The support parameters determined during the design stage based on early static data are difficult to adapt to these dynamic changes [1]. Near complex geological structures such as faults, the distribution of groundwater pressure is highly uneven. Existing conventional investigation methods find it difficult to accurately capture local high-pressure zones. If these hidden danger points are ignored during design, it will result in local weaknesses in the support structure and pose safety hazards.

2.2 Structural Damage to Engineering Structures Caused by Groundwater Corrosivity

In the design process of mine geotechnical engineering, there is a lack of effective connection

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between the assessment of groundwater corrosivity and the design of protective measures. The analysis of the chemical properties of groundwater often only focuses on simple detection of pH values and the concentrations of common ions, without delving into the synergistic corrosion mechanisms of different chemical components in long-term complex environments. In terms of material selection, designers often rely on experience to choose conventional materials without making targeted adjustments based on detailed corrosivity assessment results [2]. For example, in some mine shaft and tunnel designs, ordinary concrete is used. When facing strongly acidic groundwater rich in sulfate ions, no protective measures such as using sulfate-resistant cement or adding anti-corrosion coatings are taken. Shortly after being put into use, phenomena such as concrete spalling and steel bar corrosion appear on the shaft walls, significantly shortening the service life of the structure.

2.3 Impact of Groundwater Level Changes on Construction Safety

The prediction methods for groundwater level changes in mine geotechnical engineering design are lagging behind. They mostly rely on historical water level data and simple seasonal experience-based judgments, without fully considering the remodeling effects of mining activities on regional hydrogeological conditions. Large-scale mining dewatering can change the groundwater flow path, causing a significant drop in the regional groundwater level. However, during extreme weather events such as heavy rain, due to the limitations of the mine's topography, landform, and drainage system, local water levels are prone to sudden rises [3]. In the design of underground mining in mines, the increase in effective stress of the rock-soil mass caused by the drop in the groundwater level during the dry season is not fully considered, which can lead to rock shrinkage and cracking, reducing the bearing capacity of the foundation. This may result in uneven settlement at the bottom of the mining area, affecting the normal operation of equipment.

3. Countermeasures for the Impact of Hydrogeological Conditions on Mine Geotechnical Engineering Design

3.1 Precise Investigation to Determine Groundwater Parameters

Formulate a specialized investigation plan: Clearly define the investigation scope and depth. The investigation scope should cover the area affected by the mine geotechnical engineering and the surrounding area with a scale 1 - 2 times that of the engineering area to ensure the capture of a complete hydrogeological unit. The investigation depth should penetrate all aquifers involved in the engineering. If the excavation depth of the engineering is 50 m, the depth of the investigation boreholes should extend 30 - 50 m below the excavation surface to obtain parameters of deep confined water.

Arrange investigation boreholes according to stratum distribution characteristics: In homogeneous soil layers, the spacing between boreholes should be controlled at 50 - 80 m. In complex geological structure areas, the spacing should be reduced to 20 - 30 m to ensure the representativeness of the data. Conduct field tests to obtain basic parameters: Pumping tests: Use the steady-state pumping method. Before the test, the water level should be allowed to stabilize for more than 24 h to ensure a stable initial water level. During the pumping process, divide it into 3 - 5 drawdown stages, with each stage having a stable time of no less than 8 h. Measure and record the water inflow and water level drawdown data at each stage. Calculate the permeability coefficient using the Dupuit formula or the Theis formula, selecting the appropriate formula according to the type of aquifer. The Dupuit formula is used for unconfined aquifers, and the Theis formula is used for confined aquifers [4]. Packer tests: Use the single-point method or the five-point method. Set the test pressure at 1.2 - 1.5 times the engineering design pressure, with each pressure stage having a stable time of no less than 30 min. Record the packer water inflow and determine the permeability grade of the rock mass. Collect groundwater samples for chemical composition analysis: Detect items such as pH value, chloride ion concentration, and sulfate ion concentration, with a detection accuracy of 0.01 mol/L, providing a basis for subsequent anti-corrosion design. Establish a groundwater numerical model and conduct simulation analysis: Use professional software such as Visual MODFLOW or FEFLOW to build the model. The model grid division should meet the accuracy requirements, with a minimum grid size of no more than 5 m × 5 m. Input the stratum parameters and hydrogeological parameters obtained from the investigation, and set boundary conditions. The determination of boundary conditions should be combined with regional hydrological data to ensure consistency with actual hydrogeological conditions. Simulate water level changes and pressure distributions under different working conditions. The simulation duration should cover the engineering construction period and the initial 5 - 10 years of operation, and output the water pressure data at key locations under each working condition to provide quantitative basis for engineering design [5]. Parameter verification and correction: Compare the simulation calculation results with the initial field monitoring data. If the error between the calculated and measured water levels exceeds 5%, adjust the model parameters and re-simulate until the error is controlled within 3%.

3.2 Targeted Selection of Anti-Corrosion Materials and Processes

Formulate material selection standards based on the chemical characteristics of groundwater: Select materials according to the classification based on the assessment results of groundwater corrosivity. When the groundwater pH value is less than 4.5 and the sulfate ion concentration is greater than 2000 mg/L, sulfate-resistant cement should be used for concrete, with a cement strength grade of not less than 42.5R, and 20% - 30% of fly ash or slag powder should be added to improve the anti-corrosion performance of the concrete. When the chloride ion concentration is greater than 1000 mg/L, 316L stainless steel bars or epoxy-coated steel bars should be used for steel bars. The thickness of the epoxy coating should be controlled at 0.18 - 0.30 mm, and the coating adhesion should be not less than 5 MPa.

Conduct performance tests on materials: The anti-corrosion performance of concrete should be detected through the rapid chloride migration test (RCM), and the 28-day chloride migration coefficient should be less than 1.5×10^{-12} m^2/s. The corrosion resistance of steel bars should be detected through the neutral salt spray test, and there should be no coating peeling and the rust area should not exceed 5% within 500 h of the test [6].

Optimize the parameters of anti-corrosion construction processes:

For shaft and tunnel concrete construction: When using the shotcrete process, the pressure (should this be "spraying pressure"?) should be controlled at 0.3 - 0.5 MPa, and the spraying distance should be maintained at 1.5 - 2.0 m to ensure the compactness of the concrete and reduce porosity. Concrete curing should adopt water spray curing for no less than 28 days, and the concrete surface should be kept wet in the first 7 days to prevent early cracking.

For anti-corrosion coating construction: Before construction, the concrete surface should be treated, with a surface flatness deviation of no more than 3 mm/m. Floating dust and oil stains should be removed, and the base layer should be treated by sandblasting to reach a rust removal grade of Sa2.5. The coating construction should adopt the high-pressure airless spraying method, with a spraying speed controlled at 0.3 - 0.5 m/s. The coating should be sprayed in 2 - 3 passes, with an interval of no less than 4 h between each pass to ensure a uniform coating without missing areas.

Strengthen the design and control of grouting for water blocking: Determine the grouting material according to the permeability coefficient of the groundwater. When the permeability coefficient is greater than 1×10^{-4} m/s, use a cement-water glass double liquid grout, with a water glass concentration of 35 - 45 Be', a cement slurry water-cement ratio of 1:1 - 1:1.5, and a double liquid grout volume ratio of 1:0.5 - 1:1. When the permeability coefficient is less than 1×10^{-6} m/s, use ultra-fine cement slurry, with a cement particle size of not more than 10 μm and a water-cement ratio of 1:1 - 1:2 [7]. Set the grouting pressure at 1.5 - 2.0 times the static water pressure of the stratum. During the grouting process, adopt the sectional grouting method, with a section length controlled at 2 - 5 m. After the end of grouting for each section, maintain the pressure for 30 min. When the grouting pressure is stable and the slurry intake is less than 5 L/min, the grouting for this section can be ended. After grouting, conduct quality detection. Use the packer test to detect the grouting effect, with a packer test pressure of 80% of the design grouting pressure. If the unit length water intake is less than 0.01 L/(min·m·m), the grouting is considered qualified; otherwise, re-grouting is required to ensure effective isolation between the corrosive groundwater and the engineering structure.

3.3 Dynamic Monitoring and Regulation of Groundwater Level

Design a groundwater level dynamic monitoring system: Arrange monitoring points according to the engineering scale and hydrogeological conditions. For open-pit mine slopes, arrange one monitoring point every 50 - 100 m along the slope strike, and set 2 - 3 observation boreholes of different depths at each monitoring point to monitor the unconfined water level and confined water level respectively. For underground shaft and tunnel engineering, arrange monitoring points at the tunnel heading, both sides of the tunnel, and the shaft bottom car yard, with a spacing of 30 - 50 m. The depth of the observation boreholes should penetrate 2 - 3 aquifers above the tunnel roof [8]. Select automated water level gauges as monitoring equipment, with a measurement accuracy of ±1 mm. Set the data collection frequency at 1 time per hour, and increase it to once every 15 min during special periods. Upload the monitoring data to the monitoring center in real time through a wireless transmission system to achieve real-time monitoring of water level dynamics. Formulate a water level regulation plan: In the rainy season, the main focus of water level regulation is drainage. Calculate the drainage demand according to the historical maximum rainfall and the catchment area. The selection of drainage pumps should ensure that the drainage capacity is greater than 1.2 times the calculated value. Determine the diameter of the drainage pipes according to a water flow velocity of 1.5 - 2.0 m/s to ensure smooth drainage. Set sumps in pits and low-lying areas of tunnels, with a sump volume designed according to 5 - 10 min of the maximum water inflow and a sump spacing of no more than 50 m for easy and rapid collection of accumulated water. In the dry season, use groundwater recharge technology for water level regulation. Preferentially use treated mine water inflow as the recharge water source, and the recharge water quality should meet Class III standards of the "Quality Standard for Groundwater" (GB/T14848 - 2017). Arrange recharge wells in areas where the groundwater level has dropped significantly, control the recharge pressure at 0.2 - 0.4 MPa, and adjust the recharge volume according to the water level drop rate to ensure that the groundwater level is maintained within the range allowed by the engineering and prevent rock-soil mass shrinkage and cracking. Establish an emergency response mechanism: In underground mining design, reserve emergency drainage channels, with the cross-sectional dimensions designed according to the emergency drainage flow. The emergency drainage flow should be twice the normal drainage flow. Equip with emergency drainage equipment, including mobile drainage pumps and backup power supplies. The head of the mobile drainage pumps should cover the maximum drainage height of the engineering, and the backup power supply should have a endurance time of no less than 48 h to ensure the normal operation of the drainage equipment in case of a sudden power outage [9]. When the monitoring data shows that the groundwater level rise rate exceeds 0.5 m/d or the water level reaches the warning value, immediately should this be "activate"? the emergency response, increase the input of drainage equipment, open the emergency drainage channels, stop underground operations at the same time, and organize personnel evacuation. When the water level drop rate exceeds 0.3 m/d, activate the recharge system, increase the recharge volume, and if necessary, adjust the mining operation plan to reduce the dewatering volume, ensuring the stability of the groundwater level and safeguarding the construction safety and progress of the engineering.

4. Conclusion

Through the above analysis, it can be seen that groundwater pressure, corrosivity, and water level changes are the core hydrogeological factors affecting mine geotechnical engineering design, leading to a decline in rock-soil mass stability, structural corrosion damage, and an increase in construction safety risks respectively. The proposed countermeasures of precise investigation, optimization of anti-corrosion materials and processes, and dynamic monitoring and regulation can specifically solve the above problems. By obtaining parameters through scientific investigation, adapting materials and processes, and conducting real-time monitoring and regulation of the water level, the rationality of engineering design can be effectively improved, ensuring the safety and stability of mine geotechnical engineering during the construction and operation stages and providing references for the design of similar engineering projects.

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