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Research progress on the evolution mechanism of ground stress field and its response in major engineering construction

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Abstract: As a natural inherent stress in geological formations, ground stress is a key geological factor affecting engineering stability and safety. Based on authoritative works (e.g., *Geological Hazards and Prevention* [1], *Engineering Geomechanics* [2]) and recent research, this study systematically explores the relationship between ground stress and engineering construction, analyzes its impact mechanisms in tunnels, mines, hydropower dams, and other major projects, and reviews the latest progress in ground stress measurement technologies, predictive models, and engineering applications. The research shows that ground stress distribution directly determines engineering support design, disaster risk assessment, and construction safety management. Modern ground stress research has advanced from traditional contact measurements to intelligent, refined monitoring. This paper aims to provide theoretical references for ground stress application in engineering, improving construction scientificity and safety.

Key words: ground stress; engineering construction; stress measurement; stability; research progress

1 Introduction

Ground stress stems from natural processes like tectonic plate movement, rock mass weight, and geological structural evolution, serving as a direct reflection of rock masses' internal energy. As China's projects expand into deeper, more complex geological regions—such as the Sichuan-Tibet Railway's ultra-deep tunnels, kilometer-deep mines, and high-altitude hydropower dams—ground stress-induced engineering issues have become more acute. Per China Geological Disaster Prevention and Control Engineering Industry Association data, ground stress-triggered hazards (rock bursts, roadway collapses, slope failures) accounted for 38% of China's engineering geological disasters in the past decade, with cumulative direct economic losses exceeding 12 billion yuan. For example, the Sichuan-Tibet Railway's Lhasa-Nyingchi section tunnel saw multiple severe high ground stress-induced rock bursts, with one halting construction for over a week—underscoring the urgency of ground stress research. As an invisible constraint throughout an engineering project's lifecycle, ground stress profoundly impacts rock mass mechanical properties and structural load-bearing capacity. Neglecting its distribution easily leads to design flaws and unmanaged construction risks. Thus, in-depth research on the ground stress-engineering relationship and its latest progress holds significant practical value for safeguarding major project safety, stability, and disaster risk mitigation.

2 Core relationship between ground stress and engineering construction

Ground stress runs through the whole process of engineering construction, including survey, design, construction and operation and maintenance. The manifestation and mechanism of ground stress are quite different in different types of engineering.

2.1 Effect of ground stress on tunnel engineering

Tunnel engineering is the field most directly affected by ground stress. Excavation breaks the original stress balance of rock masses, redistributes stress, and induces disasters like rock bursts and large surrounding rock deformation. The angle between ground stress direction and tunnel axis directly determines the strength of supporting structures.

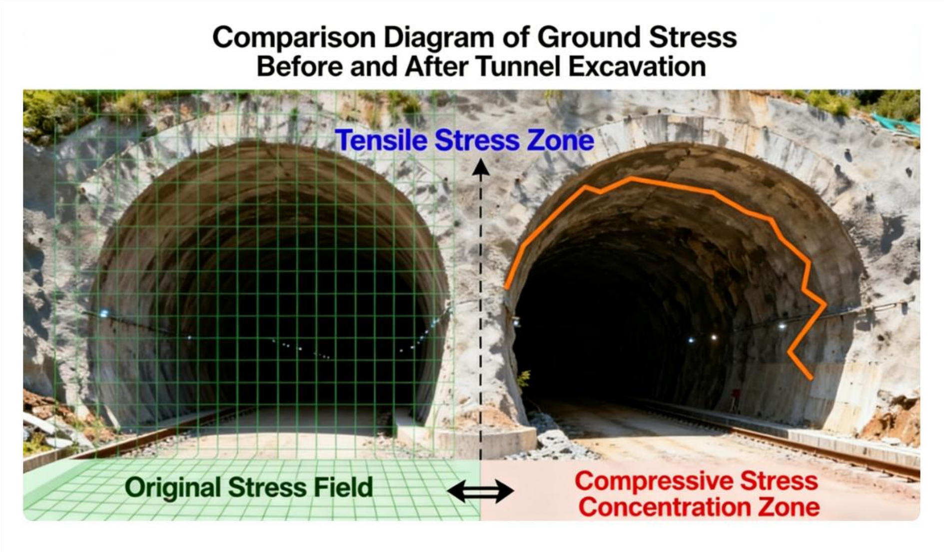

Figure 1. Comparison diagram of ground stress before and after tunnel excavation

As shown in the Figure, tunnel excavation creates stress concentration at the arch waist; when stress exceeds rock mass compressive strength, rock bursts occur. At Jinping II Hydropower Station, the auxiliary tunnel's maximum burial depth reaches 2,525 meters with ground stress up to 40MPa, leading to multiple severe rock bursts during construction—ejected rock fragments up to 1.5 meters in diameter caused significant equipment damage and project delays. Additionally, dominant stress parallel to the tunnel axis enhances surrounding rock stability, while perpendicular stress often triggers tensile failure at the arch crown and floor, requiring extra support (e.g., anchor rods, cables). Engineering practice of deep-buried tunnels in the Qinghai-Tibet Plateau and adjacent areas further confirms the impact of ground stress direction: the maximum horizontal principal stress forming a ~45° angle with the tunnel axis maximizes rock burst tendency, and perpendicular angles cause dramatic fluctuations in surrounding rock strain energy density due to lateral pressure coefficient changes [9]. Data from Pakistan's N-J Hydropower Station TBM diversion tunnel (1,785-meter depth, maximum principal stress 102.9MPa) show strong rock burst pits exceeding 3 meters deep, verifying the safety risks of tunnel engineering in high ground stress environments [12].

2.2 Influence of ground stress on mining

With mining depth increasing, deep underground stress issues are growing more prominent. High underground stress easily triggers disasters like impact ground pressure, roadway deformation, and roof collapse [6], seriously endangering mining safety. Some North China coal mines have a mining depth exceeding 1,500 meters, with frequent impact ground pressure accidents—now a key factor restricting mining safety.

Table 1. Correspondence table of ground stress values and disaster types at different mining depths

Mining depth (m)	**Ground stress value (MPa)**	**Main types of disasters**	**Typical case**
0 - 500	5 - 15	Minor deformation of the roadway and local collapse	A shallow mining area in a coal mine in Datong, Shanxi
500 - 1000	15 - 25	Top floor collapse and moderate intensity impact pressure	A coal mine in Yanzhou, Shandong
Over 1000	25 - 40	High impact ground pressure and large area deformation of roadway	A deep coal mine in Yongcheng, Henan

Geological Hazards and Prevention notes that mining-induced mined-out areas cause stress accumulation in surrounding rock; when stress exceeds rock bearing capacity, it suddenly releases as impact ground pressure [1]. Field studies at Shanxi's Changcun Coal Mine show distinct depth-dependent non-uniformity in ground stress direction—near-fault zones see maximum horizontal principal stress deviating up to 33.3°, correlated with lithologic stiffness differences and causing different compression/tension failure modes in boreholes of various rock types [10]. Additionally, ground stress affects open-pit mine slope stability: high stress induces shear fractures in slope rock masses, which may trigger landslides when disturbed by rainfall or other factors [7].

2.3 Effect of ground stress on hydropower dam project

Dam foundation rock mass stability depends directly on ground stress state. Ground stress distribution determines the foundation's bearing capacity and anti-slide stability. High horizontal ground stress may cause rock mass shear deformation, while uneven stress distribution unbalances dam body stress and induces cracks.

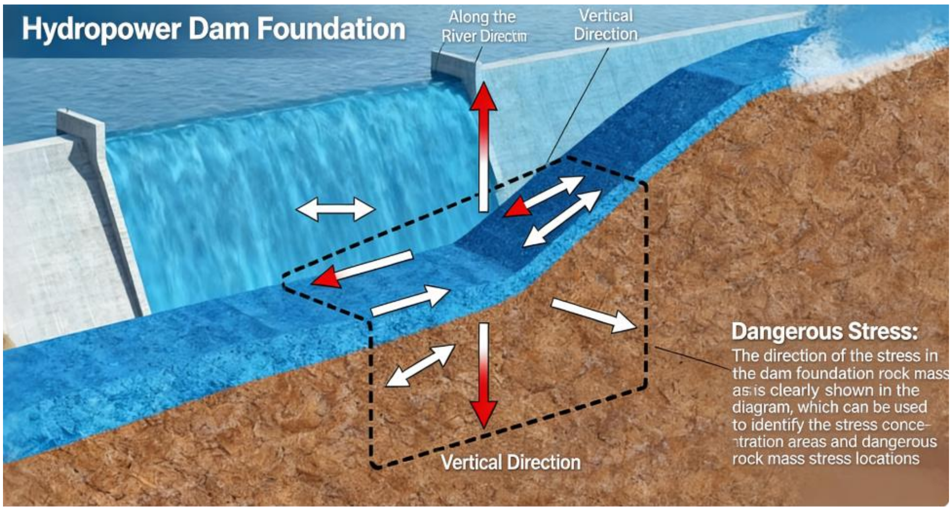

Figure 2. Hydropower dam foundation diagram

Prior to the Three Gorges Dam's construction, the research team conducted comprehensive ground stress surveys to obtain detailed foundation stress data, supporting optimization of the concrete pouring scheme and seepage prevention system design and ensuring the dam's long-term stability under complex geological conditions. Ground stress also impacts surrounding mountain stability, with high stress potentially triggering landslides that threaten dam safety. The engineering practice at Pakistan's N-J Hydropower Station demonstrates a direct correlation between the distribution of the tectonic stress field at the dam site and rockburst risks encountered in the diversion tunnels; borehole stress relief technology for ground stress measurement provides critical references for stability assessment of the dam and ancillary structures[12].

3 Recent progress in the study of ground stress

Recent years have seen rapid advancement of sensing and computer technologies, with ground stress research achieving breakthroughs in measurement technology, prediction models and engineering applications — effectively addressing the low precision and inefficiency of traditional research.

3.1 Innovation of ground stress measurement technology

Traditional ground stress measurement methods are mainly contact-based (e.g., stress relief method, hydraulic fracturing method), with drawbacks like long measurement cycles and accuracy highly influenced by rock mass integrity [3]. Distributed fiber optic sensing technology—an emerging cutting-edge focus—utilizes optical fibers' photoelastic effect for real-time, continuous rock mass stress monitoring (accuracy up to 0.1MPa), boasting strong anti-interference ability ideal for deep, complex geological environments [3]. Shanxi's Changcun Coal Mine innovatively integrated hydraulic fracturing with imaging logging, reliably determining stress magnitude and direction, characterizing reservoir stress heterogeneity, and establishing a new shallow-hole measurement paradigm [10]. Additionally, borehole imaging combined with stress measurement visualizes rock mass fracture distribution and stress concentration zones, providing key support for geostress analysis [8].

Table 2. Comparison of traditional and new ground stress measurement techniques

Measuring technique	Certainty of measurement	Measuring period	Applicable scene	Superiority	Inferior strength or position
Hydraulic fracturing	±1.5MPa	3-5 days	Shallow rock mass with good integrity	Easy to use and low cost	The impact of the fissure is significant.
Stress relief method	±1.0MPa	5-7 days	subsurface engineering, laboratory sample	The results were stable.	destructive measurement
Distributed fiber optic sensing method	±0.1MPa	real-time monitoring	Deep engineering, complex geological areas	Continuous monitoring, strong anti-interference	High equipment costs
Borehole imaging-stress coupling method	±0.8MPa	2-3 days	Various types of engineering surveys	Visual and comprehensive	The data processing is complex.

3.2 Optimization of the ground stress prediction model

Traditional geostress prediction relies mainly on qualitative geological data analysis, with relatively low accuracy [3]. In recent years, the integration of machine learning and big data technologies into geostress research has been leading to high-precision quantitative prediction models: researchers collect multidimensional data (geological structures, rock properties, topography) and use algorithms like BP neural networks and random forests to build nonlinear mappings between geostress and its influencing factors. A groundbreaking deep learning-based inversion algorithm for complex subsurface stress fields has achieved major breakthroughs—integrating discontinuous/continuous optimization learning to identify localized stress characteristics and sub-supervised learning for error control, which effectively reconstructs complex stress fields with faults and folds, greatly improving prediction accuracy for deep coal-bearing strata [11]. Liu Quansheng's team has developed a deep engineering geostress prediction model, leveraging massive datasets for training, achieved over 85% accuracy in deep mine geostress prediction [4]. Meanwhile, advances in 3D numerical simulation enable visual stress field modeling, clearly showing stress distribution in engineering zones and providing precise numerical references for design. Research in the Qinghai-Tibet Plateau and adjacent regions established multiple regression equations via 3D finite element simulations (correlating maximum horizontal principal stress direction, lateral pressure coefficients, tunnel strain energy density), which have been validated in stability assessments of multiple deep-buried tunnels [9].

3.3 Expansion of engineering application fields

Ground stress research has been widely applied throughout the entire lifecycle of engineering projects. For the Sichuan-Tibet Railway, ground stress measurement data optimized tunnel excavation plans, and "advanced pressure relief + active support" technology effectively reduced rockburst risks [5]. In deep mining, a ground stress monitoring system established an impact ground pressure early-warning mechanism for proactive disaster prediction [6]. In new energy, ground stress research at Shanxi's Changcun Coal Mine provided critical parameters for coalbed methane hydraulic fracturing—by evaluating the critical pore pressure for natural fracture reactivation, it significantly enhanced fracturing efficiency [10]. Additionally, geostress research holds great value in cross-scale engineering analysis. The cross-scale inversion method based on a five-scale geological conceptual model reconstructs geostress fields from microscopic lithology to macroscopic tectonics, offering a new perspective for large-scale project regional stability assessment. At Pakistan's N-J Hydropower Station, geostress field measurements combined with energy criteria successfully predicted tunnel rockburst levels across different depths, directly guiding construction safety management [12].

4 Conclusion and prospect

4.1 Main conclusions

Via systematic literature analysis, this study summarizes three core conclusions on geostress-engineering correlations: First, geostress is a key factor affecting engineering stability. In tunneling, mining and hydropower dam projects, it impacts safety and progress through rockbursts, impact ground pressure and rock deformation [5][6], with its direction, heterogeneity and structural coupling greatly influencing disaster risks [9][10]. Second, geostress research has made technological advances: measurement methods have evolved from traditional contact techniques to intelligent monitoring combining fiber optic sensing and imaging logging [3][8], while predictive models have advanced from qualitative analysis to deep learning-based quantitative forecasting [4][11], effectively improving stress detection accuracy in complex geology. Third, geostress research results are deeply integrated into the whole engineering lifecycle, with expanding applications in deep engineering disaster prevention and new energy development [5][6][10], providing strong support for engineering design optimization and risk management.

4.2 Future outlook

Despite significant progress in geostress research, challenges persist in achieving accurate predictions and dynamic monitoring under complex geological conditions. Future research should focus on three key areas: First, developing cost-effective, high-precision portable monitoring devices and optimizing the integrated workflow of hydraulic fracturing and imaging logging to meet diverse monitoring needs for both shallow and deep engineering projects [10]. Second, advancing interdisciplinary integration by combining geology, mechanics, and computer science to refine geostress calculation theories under multi-field coupling conditions, thereby enhancing stress prediction reliability in regions with complex geological structures[4][11]. Third, expanding geostress research applications in emerging engineering fields such as underground space development and geothermal utilization, establishing a cross-scale stress assessment system to provide technical support for high-quality development of China's engineering projects.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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