A Review of Research Methodologies for Tunnel Excavation in Fault Fracture Zones

Zexi Chen[1], Yong Hao[1,*], Luobuzaxi[2], Yang Tang[1]

[1] School of Urban Construction, Yangtze University, Jingzhou, China

[2] Tibet Tsola Kapo Industrial Group Co.Ltd., Shigatse, China

*Corresponding author

Abstract

Fault fracture zones represent typical unfavorable geological structures encountered in tunnel engineering. The inherent heterogeneity of the rock mass, structural fragmentation, and mechanical weakening characteristics within these zones readily induce disasters such as significant surrounding rock deformation, water inrushes, and mud outbursts, posing serious threats to construction safety. This paper systematically reviews three primary research methodologies for tunnel excavation in fault fracture zones: theoretical analytical methods, physical model experiments, and numerical simulation techniques. Research indicates that theoretical methods are effective for deriving key parameters, experimental methods excel in providing intuitive visualization of disaster evolution processes, and numerical methods are adept at conducting multi-factor coupling analyses. Future efforts should focus on synergistically integrating the strengths of these approaches, with an emphasis on deepening the application of intelligent algorithms and multi-field coupling models, to enhance disaster prevention and control capabilities for tunnels traversing fault zones.

Keywords

Fault Fracture Zone; Tunnel; Theoretical Analytical Method; Physical Model Experiment; Numerical Simulation Method.

1. Introduction

With the rapid development of infrastructure construction in transportation, water conservancy, and urban underground spaces in China, tunnel engineering has progressively extended into regions characterized by complex geological conditions and significant burial depths. Fault fracture zones, recognized as typical unfavorable geological structures in tunnel engineering, frequently manifest as adverse geological phenomena during construction. The weakened inter-block cementation leads to densely developed structural planes, forming intricate fracture network systems that provide pathways for groundwater storage and migration. Subjected to multi-phase geological processes[1], the rock mass within these zones exhibits pronounced heterogeneity, structural fragmentation, and mechanical weakening. When disturbed by tunnel excavation, such surrounding rock is highly prone to disasters including large deformations, collapses, water inrushes, and mud outbursts, posing serious threats to construction safety and project durability[2].Research on deformation characteristics of surrounding rock during construction holds substantial significance: it deepens the understanding of rock mass mechanical behavior while refining disciplinary theories; simultaneously, it enables engineers to accurately predict deformations, optimize construction schemes, ensure safety and quality, provide valuable references for analogous projects, and advance construction technologies toward high-quality infrastructure development.In recent years, scholars worldwide have conducted

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extensive research on mechanical response mechanisms, disaster prevention technologies, and construction optimization methods for tunnels traversing fault fracture zones. Current methodologies for studying tunnel excavation through such zones are primarily categorized into three approaches: theoretical analytical methods, physical model experiments, and numerical simulation techniques.

2. Theoretical Analytical Methods

Li Diyuan[3]applied fluid-solid coupling theory to analyze surrounding rock stability and seepage mechanisms in large-span multi-arch tunnels traversing water-rich zones, proposing enhanced drainage and support strategies.

Li Zhanglin et al.[4]derived a theoretical formula for limit support pressure at excavation faces in fault fracture zones, revealing influence laws of large-diameter shield tunneling on face stability.

Zhong Zuliang et al.[5]innovatively developed a mechanical model for water-rich fault fracture zones under multi-factor coupling and an anti-outburst rock thickness calculation model within a modified Janssen theoretical framework. Their refined model effectively characterizes how geological structure occurrence influences anti-outburst mechanisms.

Chen Yinong[6]employed elastic foundation beam theory with MATLAB-based analytical modeling to analyze longitudinal deformation of tunnels crossing fault zones.

Fu Yanbin et al.[7]introduced a multi-physics coupling model into Terzaghi's loose-media pressure theory, achieving mathematical modeling of segment mechanics in subsea shield tunnels through fault zones by expanding complex stratum loads into Taylor polynomial series. This yielded analytical solutions for longitudinal settlement and internal forces.

Sheng et al.[8]established theoretical solutions for elastoplastic analysis of arbitrarily shaped deep twin tunnels under biaxial in-situ stresses using Mohr-Coulomb and Generalized Hoek-Brown criteria.

Li Tingchun et al.[9]derived a seepage-deformation coupling model revealing water-inrush mechanisms in fault fracture zones through mechanical-dynamic theory.

Li Zongli et al.[10]advanced rock hydraulic fracturing theory, formulating critical water pressure equations for two non-destructive scenarios.

Wang Lin et al.[11]derived limit support pressure expressions via limit equilibrium theory, demonstrating that when the excavation face approaches a fault-intact rock interface within a critical distance, support pressure rapidly escalates—peaking at approximately 3.5 times that in intact rock—while failure body dip angles vary.

Guo Xiaofei et al.[12]evaluated the reliability and applicability of butterfly failure theory across diverse tunnel sections and surrounding rock conditions.

Wang Fengyun et al.[13]quantified strain-softening intensity through the tangential strain ratio at softening-residual zone interfaces. Their derived displacement equations for these zones demonstrated superior accuracy against Lee's and Cui's methods via case studies, while parametric analyses revealed strain-softening effects on plastic zone radii and displacement distributions.

3. Physical Model Experiments

Physical model experiments typically involve constructing scaled-down engineering models based on key parameters from actual projects, aiming to realistically simulate construction conditions. By employing high-precision instrumentation, researchers meticulously monitor diverse response data during simulated construction processes. Through in-depth analysis of this comprehensive dataset, detailed characteristics of surrounding rock deformation can be clearly discerned, thereby providing valuable theoretical support for practical engineering applications.Numerous scholars globally have utilized physical model experiments to investigate water and mud inrush mechanisms in water-rich fault fracture zones:

He Chuan et al.[14]conducted shaking table tests and numerical analyses to examine acceleration response characteristics of surrounding rock and tunnel structures, ground deformation, and lining force distribution in tunnels crossing fault fracture zones, revealing heightened seismic vulnerability of linings within fault zones.

Wang Hongru et al.[15]developed a physical model of fault structures combined with ABAQUS finite element analysis, elucidating deformation and failure mechanisms of tunnel linings during fault dislocation.

Zheng Kunlong et al.[16]determined similarity constants for grouting in fault fracture zones through material performance tests, developing analogous materials meeting strength requirements for tunnel pre-grouting.

Liu Xuezeng et al.[17]established a 1:50 scaled tunnel model to study deformation and failure patterns of tunnels and underlying strata under reverse fault dislocation.

Zhang et al.[18]performed large-scale model tests on tunnels traversing multiple slip surfaces in active fault zones within western China's seismic regions, analyzing structural deformation modes and damage characteristics under strike-slip motion.

Guo et al.[19]developed an innovative 3D fluid-solid coupling physical modeling system for water/mud inrush in tunnel fault zones, investigating evolution processes, damage features, and triggering mechanisms of infiltration instability in deep tunnels under complex conditions.

Zhou Xiaojieji[20]executed experimental studies on grouting reinforcement in water-rich fault fracture zones based on fluid-solid coupling principles.

Li et al.[21]created a 1:30 scaled 3D tunnel model crossing a fault zone with complementary numerical simulations using prototype parameters, assessing the influence of CD (Center Diaphragm) excavation method on tunnel stability.

Liu Guangjin et al.[22]implemented AHP-Cloud model analysis to evaluate construction risks for tunnels traversing fault fracture zones.

4. Numerical Simulation Methods

Han et al.[23]employed finite element numerical simulations to reveal how permeability contrast across geological interfaces influences seepage field distribution near tunnel faces. They proposed a novel limit equilibrium model integrating trapezoidal and prismatic elements, resolving face stability issues during tunneling through fault fracture zones under high hydraulic pressures.

Cao Jiawei [24] established a 3D geomechanical model using the 3DEC platform to investigate the combined effects of fault fracture zone presence and lateral pressure coefficient variations on tunnel stability. Through parametric modeling of multiple fault configurations, the study systematically analyzed how fault geometry governs rock mass deformation mechanisms, plastic damage evolution, and stress redistribution patterns.

Bai Songsong[25]conducted comparative numerical simulations of blasting excavation in fault fracture zones using FLAC3D and DEM software, proposing a stability control strategy combining surface and in-tunnel grouting.

Fan[26]integrated field monitoring data with numerical simulations to evaluate influences of excavation methods and fault zone characteristics on rock deformation. Results demonstrate that crown deformation intensifies with: (1) increased fault zone width or dip angle, or (2) decreased distance between fault zone and tunnel crown.

Xu[27]developed an enhanced numerical manifold method simulator to quantify combined effects of grouting range and timing on reinforcement efficiency in fault zones. Their model identifies optimal grouting parameters for fracture-sealing effectiveness.

Fu Yude[28]implemented finite element modeling with orthogonal experimental design to comparatively analyze seepage effects during tunneling through water-rich fault zones.

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5. Conclusion

This study systematically synthesizes the application status of three primary research methodologies in tunnel excavation through fault fracture zones: Theoretical analytical methods elucidate stress distribution, water-inrush mechanisms, and support force optimization through mechanical modeling, yet remain constrained by simplification assumptions. Physical model experiments visually demonstrate failure modes of surrounding rock and seepage-induced disasters during fault dislocation, providing empirical foundations for hazard mitigation-despite limitations in cost and duration. Numerical simulation techniques enable parametric analyses of fault geometry and in-situ stress environments, significantly enhancing prediction accuracy for surrounding rock stability, though reliant on input parameter reliability. Future research should prioritize: Developing integrated theory-experiment-numerics collaborative verification frameworks; Advancing intelligent algorithms for predicting surrounding rock deformation; Establishing fluid-stress-damage multifield coupling models; Optimizing grouting reinforcement and dynamic construction control technologies for fault zones. Cross-disciplinary integration will serve as the fundamental pillar for safe tunnel construction in complex geological settings.

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