Geomechanical Challenges and Engineering Solutions for Tunnel Stability in the Himalayas: A Case Study Approach

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Abstract

The Himalayan region, characterized by complex geological formations and high tectonic activity, presents significant challenges for tunnel construction. This paper examines geomechanical issues such as tunnel squeezing, stress-induced instability, and rock bursting, with a focus on hydropower and railway tunnel projects in Nepal and India. Case studies, including the Chameliya Hydroelectric Project, Parbati II Hydroelectric Project, Nilgirikhola Hydroelectric Project, and railway tunnels in the Garhwal Himalaya, highlight the impact of weak, schistose rock masses and extreme overburden pressures. Various engineering methodologies, including empirical, semi-analytical, analytical, and numerical modeling approaches, are discussed to assess stress states and deformation behavior. The study underscores the need for adaptive excavation techniques, such as the New Austrian Tunneling Method (NATM) and rock mass classification systems, to ensure tunnel stability. By integrating probabilistic analysis and advanced support systems, this research contributes to optimizing underground construction strategies in geologically challenging terrains.

Keywords: *Himalayan geology, tunnel squeezing, rock burst, stress-induced instability, hydroelectric tunnels, railway tunnels, NATM, finite element modeling, geomechanical analysis, rock mass classification, hydropower.*

Introduction

The Himalayas, one of the most tectonically active and geologically complex mountain ranges in the world, present formidable challenges for underground construction projects, particularly tunnels for hydroelectric and railway infrastructure. The region is characterized by young, fragile rock formations, high overburden pressures, active fault zones, and complex stress distributions, making tunnel stability a critical concern (Shrestha, 2021) . The combination of high in-situ stresses, geological discontinuities, and variable rock mass properties leads to severe deformation problems such as tunnel squeezing, stress-induced failures, and rock bursting (Panthi, 2011). These factors significantly impact project timelines, construction costs, and safety, necessitating rigorous engineering solutions tailored to Himalayan geomechanical conditions.

Tunnel construction in the Himalayas often encounters weak and highly schistose rock masses, including slate, phyllite, schist, quartzite, limestone, and dolomite (Neupane et al., 2024) . These rocks exhibit anisotropic mechanical properties, leading to unpredictable deformation behaviors under excavation-induced stress redistributions (Panthi, 2012) . The geological complexity is further exacerbated by the presence of thrust faults, shear zones, and highly weathered rock, as observed in projects like the Chameliya Hydroelectric Project in Nepal, the Parbati II Hydroelectric Project in India, and the Nilgirikhola Hydroelectric Project . Such conditions make conventional

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Figure 1: Challenges in tunnelling in Himalaya

tunneling methodologies inadequate, necessitating the adoption of advanced support and stabilization techniques.

One of the most critical geomechanical challenges in Himalayan tunneling is tunnel squeezing, which occurs when weak rock masses fail to withstand induced stresses, leading to excessive deformation of tunnel peripheries (Chhushyabaga et al., 2020) . The degree of squeezing is influenced by factors such as lithology, stress conditions, overburden depth, and groundwater conditions (Panthi, 2011) . In the Chameliya Hydroelectric Project, significant squeezing was observed in tunnel sections passing through phyllite and limestone formations, leading to construction delays and cost overruns (Shrestha, 2021) . Similarly, in the Nilgirikhola Hydroelectric Project, plastic deformation was prevalent due to the presence of schistose rocks, necessitating extensive support measures (Neupane et al., 2024) . Engineering studies have shown that finite element modeling and empirical classification systems, such as the Q-system and Rock Mass Rating (RMR), are essential tools for predicting and mitigating squeezing effects (Azad et al., 2024) . Another major challenge is stress-induced instability, which manifests as rock bursting, spalling, or sudden failures due to excessive tangential stresses at tunnel walls (Panthi, 2012) . In the Parbati II Hydroelectric Project, stress-induced failures were particularly severe in sections passing through Manikaran quartzite, where high in-situ stresses exceeded the rock mass strength, leading to significant excavation difficulties (Panthi, 2011) . Rock bursting incidents were also recorded in the Nilgirikhola Hydroelectric Project, with brittle rock masses experiencing catastrophic failure under high overburden pressure (Neupane et al., 2024) . The severity of stress-induced instability depends on rock type, jointing characteristics, and the magnitude of tectonic stress, necessitating precise geotechnical investigations before tunnel excavation (Azad et al., 2022) .

To address these challenges, various engineering solutions have been implemented, including empirical, semi-analytical, and numerical modeling approaches (Shrestha, 2021) . The New Austrian Tunneling Method (NATM) has been widely adopted in the Himalayas due to its adaptability to variable geological conditions (Azad et al., 2022) . NATM principles emphasize continuous monitoring and flexible support installation, allowing engineers to modify reinforcement strategies based on real-time tunnel behavior. In the Garhwal Himalaya railway tunnels, NATM was successfully applied to stabilize tunnels passing through weak rock formations, where conventional excavation methods would have been ineffective (Azad et al., 2024) .

Additionally, rock mass classification systems, such as the Q-system, RMR, and Geological Strength Index (GSI), play a crucial role in designing appropriate tunnel support systems (Azad et al., 2024) . These classification methods enable engineers to assess rock mass stability, predict deformation patterns, and select suitable reinforcement strategies. However, discrepancies between different classification systems have been observed, highlighting the need for project-specific correlations to improve predictive accuracy (Azad et al., 2024) . Recent studies have suggested refining existing classification models by incorporating probabilistic analysis to account for geological uncertainties (Panthi, 2012) .

The integration of finite element modeling (FEM) has further enhanced the accuracy of geomechanical assessments (Shrestha, 2021) . Numerical simulations provide insights into stress distributions, deformation magnitudes, and support system effectiveness under different geological scenarios. In the Chameliya Hydroelectric Project, FEM analysis using Rocscience (RS) software demonstrated that tunnel stability was highly sensitive to rock mass parameters and overburden pressure, necessitating site-specific support modifications (Shrestha, 2021) . Given the unique geotechnical conditions of the Himalayas, site-specific engineering approaches are imperative for successful tunnel construction (Neupane et al., 2024) . This includes rigorous pre-construction geological investigations, real-time monitoring during excavation, and adaptive support design strategies (Azad et al., 2022) . Moreover, the unpredictable nature of Himalayan geology underscores the importance of multi-disciplinary collaboration between geologists, geotechnical engineers, and construction specialists to develop resilient and cost-effective underground infrastructure solutions.

Stress-Induced Instability and Squeezing Rock Challenges in Himalayan Hydroelectric Tunnels

Stress-induced instability and squeezing are among the most significant challenges in Himalayan tunnel construction, particularly for hydroelectric projects. The unique geological characteristics of the region, including its young and tectonically active rock formations, create conditions where tunnels frequently experience excessive deformation, rock bursting, and failures due to high in-situ stresses. The presence of highly schistose and weak rock masses further exacerbates these issues, leading to significant engineering difficulties during excavation and tunnel support installation (Shrestha, 2021) .

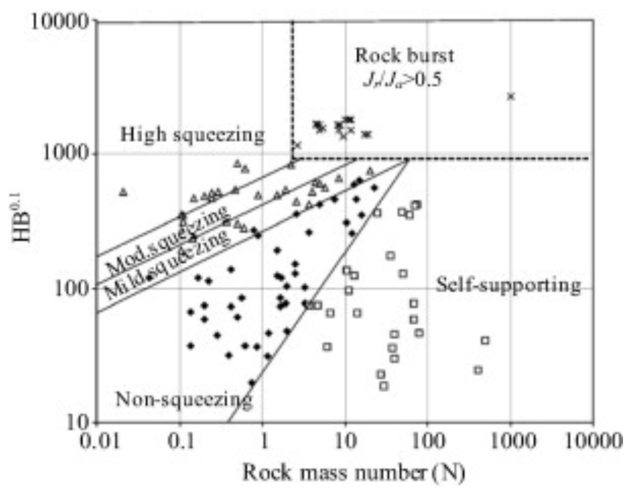

Figure 2: Influence of the Rock mass number

Stress redistribution following tunnel excavation plays a critical role in tunnel stability. When excavation occurs, the natural stress field in the rock mass is disturbed, leading to stress concentration around the tunnel perimeter. If the induced tangential stress exceeds the strength of the rock, failure occurs in the form of either brittle fracturing, such as rock bursts, or plastic deformation, known as tunnel squeezing. In the Himalayas, the latter is more prevalent in weak and highly foliated rock masses like phyllite, schist, and slate, where a plastic zone develops around the tunnel, causing excessive inward deformation of the rock walls (Panthi, 2012) . This process not only leads to significant tunnel convergence but also increases support pressure requirements, often resulting in construction delays and cost overruns.

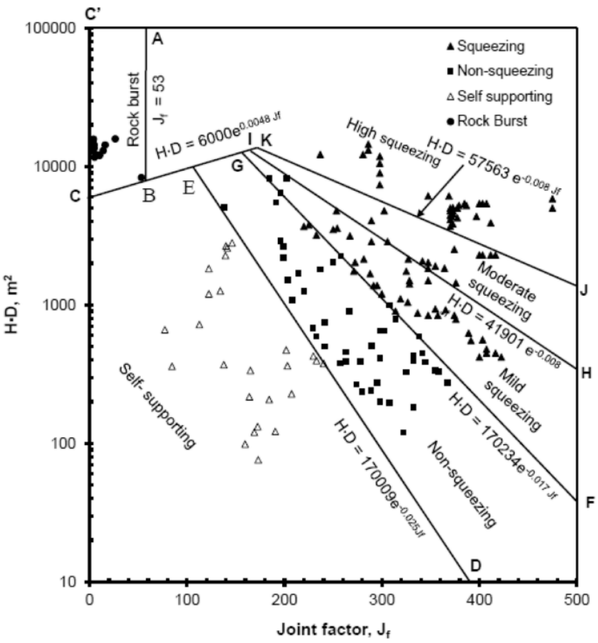

Figure 3: Influence of the Joint factor

The severity of squeezing is influenced by various factors, including the geological composition of the rock mass, the level of overburden pressure, and groundwater conditions. High overburden pressure, common in deep tunnels, contributes to squeezing by increasing vertical stress, which in turn exacerbates plastic deformation. In some cases, tunnels aligned through major fault zones experience even greater instability due to the presence of weak and fractured rock masses with minimal cohesion. Groundwater ingress further complicates stability by reducing shear strength along foliation planes, promoting further deformation and making excavation support more challenging (Neupane et al., 2024) .

One of the most affected hydroelectric projects by tunnel squeezing in the Himalayas is the Chameliya Hydroelectric Project in Nepal. The project includes a 4.067 km-long headrace tunnel that passes through a combination of sedimentary and meta-sedimentary formations, including quartzite, phyllite, schist, and limestone. Severe squeezing was encountered in tunnel sections with weak rock masses, particularly in highly foliated phyllite and fractured limestone, where tunnel convergence exceeded 30% of the original excavation diameter (Shrestha, 2021) . Finite element modeling conducted on the tunnel indicated that the degree of plastic deformation was significantly influenced by the combination of high overburden stress and pre-existing shear zones along the tunnel alignment. To mitigate squeezing, a multi-faceted approach was implemented, incorporating systematic rock bolting, steel fiber-reinforced shotcrete, and yielding steel arches designed to accommodate deformation without excessive stress accumulation. Similarly, the Parbati II Hydroelectric Project in India experienced severe stress-induced instability, particularly in sections passing through Manikaran quartzite. Unlike the Chameliya tunnel, where squeezing was the primary concern, the Parbati II tunnel encountered rock bursting due to excessive tangential stress concentration in brittle quartzite formations (Panthi, 2011) . The high overburden pressure, reaching up to 1,500 meters in some areas, resulted in frequent rock bursting events that posed significant safety risks to construction crews. The problem was further exacerbated by the tunnel's alignment along a steep valley slope, which increased horizontal stress anisotropy. To mitigate these risks, pre-

Figure 4: Challenges in tunnelling in Himalaya

tensioned rock bolts, energy-absorbing steel sets, and controlled blasting techniques were employed to minimize sudden rock ejection and stabilize the tunnel walls. Another case of severe squeezing and stress-induced instability was observed in the Nilgirikhola Hydroelectric Project in Nepal. The headrace tunnel, passing through metamorphic rock formations composed of quartzite, gneiss, and schist, experienced both rock bursting and squeezing depending on the lithological variations along the alignment (Neupane et al., 2024) . In quartzite sections, where the rock was more competent, stress concentrations led to violent rock bursts, while in schistose and foliated rock sections, excessive plastic deformation caused tunnel squeezing. The severity of squeezing in some sections reached deformation levels of up to 40% of the tunnel's excavation diameter, requiring the use of high-capacity steel rib supports, shotcrete lining with drainage systems, and continuous real-time monitoring of tunnel deformations. The methods used to assess squeezing and stress-induced failure in these projects have evolved over time, incorporating both empirical and numerical approaches. Empirical classification systems such as the Q-system, RMR, and GSI have been widely used to evaluate rock mass behavior and estimate support requirements. However, these systems often provide only a preliminary assessment and must be supplemented with semi-analytical and numerical modeling techniques for accurate predictions. The Hoek and Marinos (H/M) method has been applied in several Himalayan tunnel projects to estimate tunnel strain and determine the extent of squeezing based on competency factors of the rock mass (Panthi, 2012) . Additionally, finite element modeling (FEM) has become an essential tool for analyzing tunnel deformation patterns and optimizing support systems. In the Chameliya and Nilgirikhola projects, FEM simulations were used to validate empirical predictions and refine support strategies, leading to more effective mitigation measures. Despite these advances, squeezing and stress-induced instability remain major challenges in Himalayan tunnel construction. Future projects must integrate detailed geological and geomechanical investigations during the planning phase to better anticipate potential stability issues. Advanced monitoring techniques, such as real-time geotechnical instrumentation and remote sensing, should be implemented to track tunnel deformation and adjust support strategies as needed. Flexible support systems, including yielding steel sets and deformable shotcrete linings, should be prioritized in high-risk zones to accommodate unavoidable deformations without compromising tunnel stability.

The experience gained from projects like Chameliya, Parbati II, and Nilgirikhola highlights the critical need for adaptive engineering solutions in Himalayan tunneling. By combining empirical classification, numerical modeling, and advanced support systems, engineers can improve tunnel stability, reduce construction delays, and enhance the long-term performance of hydroelectric infrastructure in the region.

Stress State in Rock and Structures: Implications for Himalayan Tunneling and Hydroelectric Projects

The stress state in rock masses is a fundamental factor governing the stability of underground structures, particularly in the highly complex and geologically active Himalayan region. The interaction between natural in-situ stresses, excavation-induced stress redistribution, and the mechanical behavior of rock masses defines the success or failure of tunnel construction. In the context of hydroelectric and railway tunnels in the Himalayas, understanding stress distribution and rock mass response is essential for ensuring stability, mitigating deformation, and designing effective support systems (Azad et al., 2024) . The Himalayan rock masses, being relatively young and structurally complex, exhibit varying stress states depending on lithology, depth, faulting, and past tectonic events. In highly stressed conditions, rock masses can exhibit phenomena such as squeezing, stress-induced failure, and even catastrophic collapses if not properly managed during design and construction.

One of the most significant challenges associated with stress conditions in Himalayan tunneling is squeezing rock behavior, which occurs when weak rock masses, subjected to high overburden pressure, fail plastically and undergo excessive deformation. The squeezing potential is influenced by the geological strength index (GSI), rock mass rating (RMR), stress-to-strength ratio, and rock mass ductility (Neupane et al., 2024) . In many tunnels, squeezing is observed in highly schistose and foliated rock types, such as phyllite, slate, and sheared quartzite, where weak planes facilitate plastic deformation. This has been particularly evident in projects like the Chameliya Hydroelectric Project and Nilgirikhola Hydroelectric Project in Nepal, where extensive deformation required modifications to excavation and support strategies (Chhushyabaga et al., 2020) .

Stress-induced failure mechanisms, such as rock bursting and spalling, pose additional risks, especially in deep-seated tunnels excavated in competent, brittle rock masses. In tunnels passing through quartzite, gneiss, and other high-strength formations, stress concentration at tunnel walls can lead to sudden, violent rock failure due to brittle fracturing. This was a significant concern in the Parbati II Hydroelectric Project in India, where high overburden pressures exceeding 1,500 meters resulted in frequent rock bursting incidents, jeopardizing construction safety and requiring pre-tensioned rock bolts, energy-absorbing steel sets, and controlled blasting to manage stress release (Panthi, 2011) .

Stress state analysis plays a crucial role in tunnel design, particularly in determining support requirements and excavation methods. Empirical classification systems, such as RMR, Q-system, and GSI, provide a preliminary assessment of rock mass stability, while numerical modeling techniques such as finite element modeling (FEM) and discrete element modeling (DEM) enable detailed simulations of stress distribution and tunnel deformation (Azad et al., 2024) . These models help predict potential squeezing zones, stress concentration points, and optimal support configurations. In the Garhwal Himalaya railway tunnels, numerical simulations have been instrumental in correlating rock mass classifications with actual stress responses, improving the reliability of geomechanical assessments and excavation planning (Azad et al., 2024) .

Construction methodologies must be adapted to varying stress conditions encountered along tunnel alignments. The New Austrian Tunneling Method (NATM) has been widely implemented in Himalayan tunnel projects due to its flexibility in dealing with stress redistribution. NATM emphasizes controlled deformation and support adaptation based on real-time monitoring data, allowing for dynamic adjustments in reinforcement strategies (Chhushyabaga et al., 2020) . In squeezing conditions, yielding steel arches and deformable shotcrete linings are used to accommodate stress redistribution without excessive damage to tunnel structures. Conversely, in rock bursting-prone areas, rock reinforcement techniques such as systematic bolting and mesh-lining are critical in preventing high-energy rock failures (Panthi, 2012) .

Groundwater pressure significantly influences stress conditions within rock masses, exacerbating tunnel deformation and stability issues. High-pressure water ingress can weaken jointed rock masses, reducing effective stress and increasing the likelihood of squeezing or collapse. In projects such as the Nilgirikhola Hydroelectric Project, extensive pre-excavation grouting was required to seal water-bearing fractures and mitigate hydrostatic pressure effects (Chhushyabaga et al., 2020) . Effective drainage systems, including horizontal drain holes and dewatering wells, are crucial in controlling groundwater flow and maintaining tunnel integrity.

Another crucial aspect of stress analysis in tunnel design is the correlation between different rock mass classification systems to enhance predictive accuracy. Recent studies on railway tunnels in the Garhwal Himalaya have focused on developing inter-correlations between RMR, Q-system, and RMi to refine tunnel support design (Azad et al., 2024) . These correlations have improved the reliability of geotechnical assessments by aligning empirical classification outputs with numerical stress analysis results, enabling engineers to make more informed decisions on excavation and support strategies. However, discrepancies still exist in certain classification relationships, particularly when applied to highly variable metamorphic rock conditions in the Himalayas, necessitating further refinement of predictive models.

The stress state within underground structures is also influenced by regional tectonics and seismic activity, which can induce additional stress variations over time. The Himalayas, being one of the most seismically active regions in the world, experience frequent tectonic movements that can alter stress distributions within rock masses. Long-term stability assessments must incorporate seismic risk evaluations, particularly for hydroelectric tunnels that house critical infrastructure such as powerhouses and surge shafts. Seismic-resistant design features, such as reinforced tunnel linings and flexible support systems, are necessary to withstand dynamic loading and prevent tunnel damage during earthquakes (Azad et al., 2024) .

Real-time monitoring and instrumentation are indispensable for managing stress-related risks during tunnel construction. Instruments such as stress meters, strain gauges, convergence meters, and ground-penetrating radar provide continuous data on rock mass behavior, allowing for early detection of stress anomalies and timely intervention. Adaptive construction practices based on monitoring feedback have proven effective in mitigating stress-induced failures, as seen in the Chameliya and Parbati II projects, where systematic instrumentation helped engineers refine support strategies in response to evolving stress conditions (Panthi, 2012) .

In conclusion, stress state management in Himalayan tunnel construction is a multifaceted challenge requiring an integrated approach that combines empirical classification, numerical modeling, adaptive excavation techniques, and real-time monitoring. The complex interplay between in-situ stresses, rock mass properties, and construction methodologies necessitates site-specific solutions tailored to each project's geological conditions. By leveraging advanced geomechanical analysis tools and adaptive support systems, engineers can improve tunnel stability, reduce construction risks, and enhance the long-term performance of hydroelectric and railway infrastructure in the Himalayas. Future research should focus on refining stress prediction models, improving rock mass classification correlations, and developing more resilient construction techniques to address the unique challenges posed by Himalayan geology.

Design and Construction of Hydroelectric Tunnels in the Himalayas: Challenges and Engineering Solutions

Designing and constructing tunnels in the Himalayas for hydroelectric projects requires careful planning, robust engineering methodologies, and adaptive construction techniques due to the challenging geological conditions. The complex interaction between in-situ stresses, highly schistose rock masses, and groundwater ingress necessitates an integrated approach that combines empirical classification systems, numerical modeling, and real-time monitoring to ensure tunnel stability and structural integrity. The New Austrian Tunneling Method (NATM) has proven to be an effective approach in dealing with the ever-changing geological conditions of the region, as it allows for a flexible design and construction strategy based on continuous assessment of ground behavior (Azad et al., 2022) .

Figure 5: Historical tunnel construction in Himalaya

One of the key aspects of tunnel design in the Himalayas is rock mass characterization, which serves as the foundation for selecting appropriate excavation and support methods. The Rock Mass Rating (RMR), Q-system, and Geological Strength Index (GSI) are widely used to assess rock mass conditions and determine necessary reinforcements. The presence of fault zones, shear bands, and highly weathered rock complicates tunnel stability, requiring the integration of additional geotechnical investigations such as borehole drilling, seismic tomography, and geophysical surveys (Chhushyabaga et al., 2020) . In many Himalayan tunnels, sections passing through weak phyllite, schist, and fractured quartzite exhibit extreme squeezing behavior, necessitating modifications to initial support designs.

Excavation methodologies must be adapted to the geological conditions encountered. The conventional drill-and-blast method remains the most commonly used approach in the region due to its adaptability to varying rock strengths and discontinuities. However, controlled blasting techniques are essential to minimize damage to the surrounding rock mass and reduce stress concentration, which can lead to tunnel deformation or collapse. In weak rock formations, mechanical excavation using tunnel boring machines (TBMs) is often not feasible due to the unpredictability of ground conditions and the presence of mixed lithologies that can lead to cutter wear and operational inefficiencies (Azad et al., 2022) .

Support systems play a crucial role in maintaining tunnel stability and preventing large-scale deformation. In faulted and sheared zones, a combination of steel ribs, rock bolts, and shotcrete linings is commonly employed to provide structural reinforcement. Case studies from hydroelectric projects in Nepal and India have demonstrated the effectiveness of yielding support systems that allow controlled deformation while preventing excessive closure. The headrace tunnel of the Kali Gandaki Hydroelectric Project, for instance, required extensive reinforcement due to its alignment through highly deformed phyllite and graphitic schist. Here, a combination of steel fiber-reinforced shotcrete (SFRS), lattice girders, and fully grouted rock bolts was used to mitigate tunnel convergence and maintain stability (Chhushyabaga et al., 2020) .

In addition to empirical and observational methods, numerical modeling has become an essential tool for optimizing tunnel design and construction. Finite Element Analysis (FEA) and Discrete Element Modeling (DEM) are widely applied to simulate stress distributions, predict deformation patterns, and evaluate the effectiveness of different support systems. The use of software such as RS2 (Rocscience) and FLAC3D enables engineers to analyze complex ground-structure interactions and refine support designs based on real-time monitoring data. In the Parbati II Hydroelectric Project, for example, numerical simulations helped identify critical stress zones where additional reinforcement was required, thereby preventing unexpected failures during excavation (Azad et al., 2022) .

Groundwater control is another significant aspect of tunnel construction in the Himalayas, as high permeability rock formations and fractured zones often lead to excessive water inflow. Drainage systems, including horizontal drain holes and dewatering wells, are implemented to reduce hydrostatic pressure and prevent water-induced weakening of the rock mass. In some cases, pre-grouting with cement or chemical injections is necessary to seal water-bearing fractures and improve ground conditions before excavation begins. The Nilgirikhola Hydroelectric Project faced severe groundwater ingress in its headrace tunnel, requiring extensive pre-excavation grouting and waterproof shotcrete lining to maintain tunnel integrity (Chhushyabaga et al., 2020) .

Adaptive construction strategies are vital for ensuring project success in the highly unpredictable geological environment of the Himalayas. Real-time monitoring systems, including extensometers, load cells, and convergence meters, provide continuous feedback on tunnel behavior, allowing engineers to modify excavation sequences and support installations as needed. The NATM approach, with its emphasis on observational tunneling and flexible support systems, has been instrumental in managing construction risks and optimizing tunnel stability under highly variable conditions (Azad et al., 2022) .

Ultimately, the design and construction of hydroelectric tunnels in the Himalayas require a multi-disciplinary approach that integrates geotechnical investigations, empirical rock mass classification, advanced numerical modeling, and real-time monitoring. Lessons learned from previous projects underscore the importance of adaptive excavation methods, robust support systems, and proactive groundwater management in mitigating geomechanical risks. By leveraging a combination of traditional and modern engineering techniques, future tunnel projects in the region can be executed more efficiently, ensuring long-term structural stability and operational reliability.

Conclusions

The management of stress conditions in rock masses and underground structures is a critical aspect of tunnel construction, particularly in geologically complex and tectonically active regions like the Himalayas. The interaction between in-situ stresses, excavation-induced stress redistribution, and rock mass properties dictates the stability and longevity of hydroelectric and railway tunnels. As evidenced by case studies such as the Chameliya, Parbati II, and Nilgirikhola hydroelectric projects, severe squeezing and stress-induced failures can compromise tunnel integrity if not properly managed. The implementation of empirical classification systems, numerical modeling techniques, and adaptive construction methodologies has proven essential in mitigating these risks. However, despite advancements in geotechnical analysis, significant challenges remain, particularly concerning the variability in rock mass response across different lithological and structural conditions. The development of inter-correlations between rock mass classification systems, as studied in the Garhwal Himalaya railway tunnels, has provided valuable insights into improving predictive accuracy and support design, but further refinement is needed to enhance applicability across diverse geological settings.

Future research and engineering practice should focus on refining stress prediction models, improving empirical classification correlations, and integrating real-time monitoring data into decision-making processes. The continued evolution of construction techniques, including the use of more sophisticated yielding support systems, seismic-resistant tunnel linings, and advanced groundwater management strategies, will be essential in ensuring the long-term stability of underground structures in the Himalayas. Additionally, the impact of regional tectonics and seismic activity on stress distribution must be further investigated to enhance tunnel resilience against dynamic loading. By adopting a multi-disciplinary approach that combines geological, geotechnical, and structural engineering expertise, tunnel projects can be executed with greater efficiency and safety, contributing to the sustainable development of hydroelectric and railway infrastructure in one of the most challenging terrains in the world.

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