Advancements in Tunnelling: The Role of Engineering Geology in Design and Construction over the Last 30 Years

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Abstract: Over the past three decades, tunneling has advanced significantly through integration of engineering geology into design and construction. Modern practices emphasize understanding critical failure mechanisms rather than relying solely on classification systems. Developments in geological investigation, rock mass classification (RMR, Q-system, GSI, Hoek–Brown), numerical modelling, and behavior-based approaches, including the Tunnel Behavior Chart and GCBS, have improved predictive assessments and support design. Case studies highlight the influence of structural anisotropy, stress conditions, and groundwater on tunnel behavior. Future integration of artificial intelligence promises real-time adaptive design, optimizing support systems and enhancing safety, efficiency, and cost-effectiveness in complex underground construction.

Keywords: ***Tunneling, Rock mass classification, Behavior-based design, Tunnel support systems, Artificial intelligence.***

Introduction

Over the last three decades, the field of tunneling has witnessed remarkable advancements driven by a deeper understanding of engineering geology and its integration into design and construction processes. This presentation explores how developments in geological investigation, rock mass classification systems, and numerical modelling have reshaped modern tunneling practice (Hoek and Marinos, 2000; Marinos et al., 2005).

The study emphasizes that geological knowledge cannot be reduced to a single rock mass rating value; rather, successful tunnel design begins with the identification and understanding of the most critical failure mechanisms (Bieniawski, 1976; Marinos, 2007). Once these mechanisms are defined, appropriate design parameters can be selected, followed by realistic analysis of temporary support systems tailored to the expected ground response (Marinos, 2012; 2014).

The paper traces the evolution from early empirical systems such as the Rock Mass Rating (RMR) and Q-system to more comprehensive methodologies like the Geological Strength Index (GSI) and the Hoek–Brown failure criterion, which better link geological observations to mechanical parameters (Marinos, 2017; Marinos and Carter, 2018). These frameworks, supported by advances in site investigation and numerical tools, have enabled engineers to move beyond simplified classifications toward behavior-based design approaches.

The introduction of the Tunnel Behavior Chart (TBC) and the Ground Characterization, Behavior and Support (GCBS) system have further allowed for predictive assessments of tunnel performance by integrating rock mass fabric, intact strength and overburden depth.

Case Studies and Behavior-Based Analysis

Drawing upon data from hundreds of tunnels constructed across diverse geological settings in Alpine Mountain belts, the presentation presents detailed examples of tunneling behavior in tectonized, altered and weathered formations (Hoek et al., 2005). Each case highlights the necessity of coupling geological interpretation with engineering analysis to manage complex rock mass responses such as squeezing, chimney-type, raveling, or wedge failures.

The findings underscore that even rock masses with equivalent classification values may exhibit markedly different tunnel behaviors depending on their structural anisotropy, stress conditions and groundwater influences. Hence, we cannot depend solely on geotechnical classification systems.

Tunnel Support Design and Engineering Geological Integration

Furthermore, the paper highlights that the selection and design of tunnel support measures must be firmly guided by the identified behavior mode of the ground, which in turn depends on a sound understanding of the engineering geological model, the geotechnical properties of the rock mass, and the magnitude of the overburden.

Support design is not a prescriptive exercise based solely on classification ratings but a process that must directly respond to the dominant failure mechanism, whether stress-driven (squeezing or shear-type) or gravity-driven (wedge, chimney, or ravelling-type). For isotropic rock masses where deformation is stress-induced, the design should rely on rock mass parameters derived from systems such as the GSI and

Hoek–Brown criterion to define shotcrete thickness, rock bolt patterns and yielding elements that accommodate controlled convergence. Conversely, in anisotropic or discontinuous rock masses governed by joint orientation and persistence, stabilization requires reinforcement and confinement measures that counteract block rotation and detachment, such as systematic bolting, steel sets, or forepoling.

The overburden depth plays a crucial role in defining confinement and the transition between gravity and stress-dominated failure modes, influencing the stiffness and timing of support installation. Ultimately, the principal underpinning modern tunneling practice is that support systems must be behavior-based developed from a comprehensive geological and geotechnical understanding that allows timely adaptation during construction, ensuring stability, safety and cost efficiency. Geotechnical classifications can always contribute, either by using them in their core range of applications or as a means of classification a rock mass achieving a sound communication of all parties in design, construction and supervision.

The presentation advocates an integrated, behavior-oriented approach to tunnel design, where engineering geological insight forms the foundation for both numerical modelling and support selection. This methodology ensures that the inherent variability of geological materials is captured within the design process, leading to safer, more economical, and adaptable tunneling solutions. The last 30 years thus mark a paradigm shift from empirical categorization toward a comprehensive understanding of ground–structure interaction governed by geological reality.

Future Perspectives and Conclusion

Looking ahead, artificial intelligence (AI) is poised to play a transformative role in achieving these same objectives within the next decade. By integrating vast datasets from geological mapping, geotechnical testing, instrumentation and real-time monitoring.

AI can help refine and continuously update the engineering geological model throughout the design and construction stages. Machine learning algorithms can be trained to recognize patterns linking specific geological and geotechnical conditions to observed tunnel behaviors, enabling predictive identification of potential failure modes before excavation.

Moreover, AI-assisted numerical modelling could automatically calibrate material parameters based on sensor feedback, improving the reliability of stress–deformation analyses and optimizing support design in real time. Autonomous data interpretation systems could also assist engineers in adaptive decision-making recommending modifications to excavation sequences, support types, installation timing as ground conditions evolve. Ultimately, the integration of AI in tunneling will enhance the synergy between geological understanding, analytical modelling, and field observation, leading to safer, more efficient and truly adaptive underground construction practices.

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