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Original Article

Predictive Estimation of TBM Torque and Thrust for Tunnel Stability in Challenging Environments

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Abstract *- Uncertainties associated with tunnelling in geotechnically complex and structurally heterogeneous formations arise due to the unpredictable nature of rock masses, faulted zones, and high groundwater pressures. These ground behaviors result in unstable faces at the tunnel entrance, extensive ground deformation, and TBM jamming, which may hamper construction safety and project duration. Previous literature addressed the framework by torque and thrust independently, which affects tunnel stability indicators and ignores the hydromechanical coupling. To address this research gap, this study outlines a predictive model for estimating key TBM operational parameters, Torque (Tq) and Thrust (Th), in relation to the diameter of the tunnel and specific geomechanical and hydrogeological properties of the site. The Finite Element Analysis (FEA) based methodology was used in estimating these parameters, which represent the interaction between the ground and the TBM, considering the effect of overburden stress, rock mass strength, and groundwater pressure. A series of parametric studies was conducted for different tunnel diameters ranging from 6 to 16 m under various water heads to demonstrate the non-linear relationship between the forces required to operate a TBM. The observed result found that the increase in force required to operate a TBM is significantly greater when there is a higher hydrostatic pressure. The findings were validated using actual geological data collected from a case study of a Himalayan tunnel project, which represents a typical challenging environment for tunnelling. The developed model is a useful decision-making aid for pre-construction planning, selecting TBMs, and managing risks and will be applicable to other mountainous and tectonically active regions that exhibit similar geological complexities.*

Keywords *- Excavation Face stability, TBM entrapment, Risk Mitigation, TBM Torque, Machine Thrust.*

1. Introduction

One of the hardest parts of the development of underground infrastructure is tunneling in the geologically unfavorable and structurally disrupted ground conditions [10]. Examples of such ground conditions include heterogeneous lithologies, variable rock mass quality, active fault zones, and high in-situ stress regimes [1, 3, 4, 6]. All these factors constitute a severe risk to excavation stability as well as Tunnel Boring Machine (TBM) operation and can cause deformation-related failure, face collapse, and/or jamming of the TBMs in such a challenging environment [2, 5, 7]. The challenging environment is defined as a geological formation that comprises highly variable geological structure and geomechanical properties. The steepest geological and geodynamic history and ongoing geological processes offer the greatest extreme limitations to tunneling worldwide in the mountainous landscapes and tectonically active zones. The Himalayan mountain belt serves as a good example of such constraints, which include a diverse stratigraphy, many litho-tectonic units, and extensive structural discontinuities [9, 10]. The area is further subdivided into a few large thrust systems, with the Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), and Main Central Thrust (MCT) being the main thrust systems. Along with the tectonic aspects mentioned, the long geologic history of the area of orogenesis and sedimentation has led to a rock mass construction that is likely to be squeezy, fault sheared, and inflow of groundwater. The above geological complications contribute to the uncertainty that comes with the building of the tunnels and increase the chances of delays in the operation and mechanical breakdowns [11-14].

Lesser Himalayan corridor. Past tunneling works have demonstrated the boundaries of traditional excavation techniques and the functional inefficacies of mechanized mechanisms in this type of geology [15-18]. Past experiences of tunneling that have been done in this area have recorded incidents of unstable faces, over deformation, entrapment of equipment, and protracted downtime because of unknown processes in the ground. Although TBM designs and capabilities have been technologically advanced, the implementation of TBMs in tectonically active and structurally heterogeneous rock masses remains a serious problem. The challenges are not limited to handling weak or fractured rock, but also the sudden changes between competent and very deformable rock with relatively short distances [19-24].

Much of the historical research in this field has been on post-failure studies or descriptive studies of the TBM performance in complicated geological environments. Despite the fact that some researchers have already applied numerical simulation tools (e.g., PLAXIS and FLAC2D) in the case of modeling the behavior of the ground during tunnel excavation, much remains to be done in terms of relating TBM operational parameters (i.e., Torque (Tq) and Thrust (Th)) to the tunnel geometries and geomechanical properties before the excavation process can take place. The hydrological effects (e.g., the effects of the water head over the tunnel crown) have traditionally been neglected in most previous models, even though the hydrological component has been acknowledged as capable of causing the initiation of tunnel instability [25-28, 30, 51, 52].

To fill this research gap, the authors came up with an analysis of Finite Element Analysis (FEA) to model the torque and thrust of a TBM relating to the diameter of the tunnel and the unique ground conditions at the site. The model takes into account such critical geological parameters (e.g., mass strength of rocks, deformation modulus, and in-situ stresses) and hydrological parameters (e.g., pressure of groundwater above the tunnel alignment). The authors opted to apply the model to the Lesser Himalayan region as a case study in order to test it due to its known geological complexity and tunneling challenges in the past. The model was driven by site-specific information obtained at the Rishikesh-Karnaprayag railway tunnel alignment.

Another peculiar feature of this study is the non-linearity between TBM working forces and the tunnel diameter. These observed relationships imply the requirement of early forecasting of TBM performance and the stability of excavation. With the increased size of the tunnel, the area of the face and contact between the ground and the structure grow exponentially, and the risk of jamming of the machines and deformation of the ground also increases exponentially. Another factor that is studied is the influence of water head on deformation behavior of the tunnel, especially the crown settlement and invert uplift, with the importance of the hydrostatic loading on the machine-ground interaction.

The research offers a better insight into TBM-ground behavior in structurally complicated and water-affected settings and can be proactively employed as a means of equipment choice, tunneling plans, and risk avoidance. Even though validation on the Himalayan geology was the framework by which the authors chose to undertake their studies, the model can be generalized to other tectonically active and geologically heterogeneous areas that can face similar mechanized tunneling challenges.

By bringing together geological, geotechnical, and hydrologic parameters and modeling them within a predictive modeling framework, this study facilitates the state-of-the-art in the evaluation of TBM performance and estimation of tunnel stability. The findings of the study will help design engineers and project managers make wise decisions in the planning and implementation of the tunnel projects and eliminate the risks of expensive delays and dangers in the unfavorable ground conditions.

2. Literature Review

Development of Tunnel Boring Machine (TBM) torque and thrust prediction has been continuously progressing during the last decades, preconditioned by the enlargement of underground construction facilities and demand towards excavation safety, efficiency, and stability. TBMs have revolutionized mechanized tunnel construction through the ability to offer continuous excavation with lesser disturbance when compared to conventional drilling-and-blast systems. Their operational efficiency and structural safety, however, are very sensitive to proper estimates of cutterhead torque and thrust forces, which directly indicate the behavior of ground machine interaction and the stability of the tunnel [53, 54]. The nonlinear co-relationship among geological parameters and operational variables in the complex geological settings that include heterogeneous rock masses, fault zones, karst cavities, weathered formations, and different pressures of groundwater present a major uncertainty in predicting TBM performance [55, 56] These intricacies have driven comprehensive studies in terms of empirical, analytical, numerical, and data-based studies [57, 58, 61].

Empirically based prediction models. Early prediction models were largely ad hoc, based on field observations and laboratory experiments on rock cutting, which were developed in the 1970s and 1980s [59, 60, 62]. In general, these early empirical formulations were a correlation of torque and thrust with properties of the rock mass, which included uniaxial compressive strength, designation of rock quality, and machine diameter [63-67]. Even though these models offered some practical design advice, they were very project-specific and not applicable across geological environments. With the growth of ground conditions in the construction of tunneling projects in more difficult areas, the shortcomings of a purely empirical approach became more apparent.

Later, scientists turned to the analytical methods of modeling, based on rock mechanics and the theory of machine interaction. Q. Zhang et al. [68, 69] came up with a theoretical framework to predict loads on shield tunneling machines by considering interbedded soil and rock ground conditions and applying the concept of mechanical decoupling to assess the cutterhead-ground interacting stress. They showed that the geological, structural, and operational parameters have a combined effect on acting thrust, as well as the importance of including overburden stress and cutterhead topology. On this analytical basis, [70, 71] developed a modeling framework for predicting thrust in EPB TBMs working at different geological conditions. Their method also improved the decoupling ideas of mechanics and tested the model with data from various subway projects, therefore, leading to more systematic thrust estimation. Trying to make the system more adaptable in hard rock conditions [72], integrated analytical formulas and system, and came up with hybrid models to predict the cutterhead torque and thrust of EPB machines with disc cutters. Their findings showed that they have better accuracy, especially when there are dense limestones in the rock, and the possibility of incorporating fuzzy logic in traditional theoretical models. In addition to these developments, the author [73] developed a sensitivity analysis to assess the effect of structural, control, and geological parameters on TBM performance of various prediction models. Their results showed that geological parameters have a dominant effect on cutter life and have a considerable impact on torque-thrust behavior, which supports the significance of using suitable prediction frameworks for different ground conditions. Their theoretical strength notwithstanding, the analytical methods were limited in their simplifying assumptions and in their lack of capacity to capture the heterogeneous geological variability.

The development of computational performance in the late 1990s and early 2000s made possible the introduction of numerical modeling methods, especially the finite Element (FEM) and Discrete Element (DEM) methods, to simulate TBM-ground interaction in detail [69]. J. Nimic [74] has established a real-time system using a meta model system to study the cutterhead excavation system of EPB machines, which involves the intricate contact mechanics and interaction between soil and particles. Author [55] proposed dynamic numerical modeling to assess the time-dependent cutterhead loads, which considers the redistributed stress and changing loads during the excavation. [56] Utilized an algorithm to model hard rock excavation using the double-shield TBMs, which provides a better representation of a jointed rock mass. Equally, [61] were able to optimize disc cutter spacing in jointed hard rock with discrete element modeling to show that numerical models can be used to guide the design of cutterheads. Hybrid simulation surrogate modeling strategies were further developed. [60, 64] combined FEM with meta-models to provide the capability to conduct real-time steering and model update during the tunneling procedure to bridge the gap between the high-fidelity simulation and operational aspects. Recently, [65] integrated machine learning simulation to come up with surrogate numerical prediction techniques of TBM positioning. Even though numerical modeling provided an important contribution to the physical representation of ground-machine interactions, they were still highly computationally intensive and required a significant calibration effort, making them impractical in real-time decision-making in highly variable geological environments.

The spread of sensor technologies and digital surveillance in contemporary TBM was a shifting point in predictive research, allowing both the development of information-based machine learning models [60, 64]. The initial uses were the artificial neural networks, support vector machines, and neuro-fuzzy hybrid systems. The feasibility of AI-based TBM performance prediction in the rock tunneling setting was demonstrated [75], and an imperialist competitive algorithm was proposed [76], resulting in high predictability of the model. In their study, Haowen et al. [77] used regression, LSTM, fuzzy systems, and multilayer perceptron models to forecast EPB operational parameters, which led to enhanced face stability control in urban tunneling. The second stage of evolution was marked by deep learning models that can learn the temporal dependencies on the TBM data of operations. [78] Proposed an intelligent assistant driving system based on deep learning to identify the grade of rocks automatically, and also to modify the tunneling parameters. Zhang et al. [79] implemented bi-GRU-ATT networks on real-time prediction of torque and thrust, as they were currently shown to perform better than the classical theory. In deep-buried tunneling, Y. Chen, et al [80] used a prediction framework with LSTM to obtain both spatial and temporal features, which resulted in high predictive accuracy. Xu et al. [81] suggested the concept of spatio-temporal feature fusion methods in order to improve real-time prediction of parameters, whereas Haowen et al. [77] confirmed the use of LSTM architectures to predict tunneling parameters. Zhang et al. [78, 84] took the methods further to include bidirectional recurrent structures and optimization methods like particle swarm optimization to improve the quality of prediction.

New studies have been more inclined towards hybrid and ensemble learning systems. Bogani [82] also combined Hidden Markov Models with ensemble learning in order to classify and predict the torque and thrust states under complex geological conditions. Liang et al. [83] used the GA-BPNN model for underwater shield tunneling, which enhanced the accuracy of prediction in high water pressure areas. A hybrid LSTMXGBoost model hypothesized by fotlanxqsj [84] has achieved strong generalization to predict time-series, especially on high-permeability soils. Chen et al. [85] designed the TransTP network of real-time multiperiod prediction based on temporal attention mechanisms, and Fan [86] enhanced the use of knowledge-based performance indexes in the Random Forest models. Fu et al. [87] presented transfer learning models to solve the small amount of available data in new tunneling projects to improve flexibility. Zhang et al. [88] used adaptive genetic algorithms to optimize the LSTMMLP hybrid networks to achieve further accuracy. The latest stage of evolution is the NSA-CHG intelligent prediction framework that is offered as a proposal [89], which combines both sparse attention mechanisms and physics-enhanced modeling in order to obtain high prediction and real-time optimality in the complicated geological setting. [90] used a combination of learning algorithms to ultra-large diameter slurry shield tunnel TBMs that cross rivers and proved to be resistant to faulted and karst conditions. On the same note, [91] created estimation models in mixed-face strata. 1 in ultra-large section EPB pipe jacking machines. Author [42] came up with elastic-network-based torque determination systems to enhance computational power. Context-aware and stage-specific prediction models have also been highlighted by research. The stage-adapted Random Forest model demonstrated the significance of updating prediction algorithms with the advance of tunneling, and Liu et al. [64] suggested LSTM-SVM frameworks with the classification of the surrounding rocks, as they pointed out that with a proper geological characterization, the prediction of the torque or thrust can be realized reliably.

All in all, the literature shows that there was a definite evolutionary trend of empirical rules, followed by analytical theory, numerical simulation, machine learning, and eventually hybrid data-physics fusion frameworks. Although current deep learning architectures are accurate and can be applied in real-time, there are difficulties in ensuring the generalization of such systems in a wider geological setting, incorporating the effect of hydromechanical coupling, and improving interpretability to address safety-critical tasks. Despite the significant advances that have been made in the process of forecasting TBM torque and thrust using empirical, analytical, numerical, and data models, various research gaps are still critical, especially where the stability of the tunnel in extreme conditions is concerned. Current analytical and computational models are physically rigorous but simplified by assumptions and computationally intense, and therefore may not be applicable in heterogeneous geological and hydrogeological environments. On the other hand, new machine learning and deep learning models have been shown to be very predictive, but most of them tend to be heavily reliant on massive amounts of data from the project being analyzed, and also have poor generalization aspects when used in new tunneling activities with different geological backgrounds.

In addition, it is found that the majority of current research is mainly concerned with the accuracy of the predictions made regarding the torque and thrust, whereas the impact on the predictive outcomes in relation to the stability indicators in the tunnels is relatively low (face deformation, stresses in the linings, convergence processes, and the potential jamming or collapse). The effect of coupled hydromechanical processes, such as the variations in groundwater pressure, the weakening caused by seepage, and the degradation of rock mass with time, is also not effectively incorporated into the existing prediction models. Also, not many of the models incorporate in a systematic manner the real-time uncertainty in geology, mixed-face conditions, and sudden change of lithology, which are important aspects that determine instability in complex underground environments. Besides, advanced deep learning models cannot be broadly applied to safety-critical tunneling projects, as their interpretability and physical transparency are not yet adequate. Minimized incorporation of physics-based constraints, field monitoring feedback, and adaptive learning mechanisms also limits their credibility in changing ground conditions.

Considering such limitations, it is evident that there is a necessity to create a combined predictive framework to integrate physical knowledge, numerical analysis, and the most recent machine learning algorithms to predict both TBM torque and thrust accurately and link them directly to tunnel stability in the challenging conditions. This framework sought to include the effects of hydromechanical coupling, real-time monitoring data, and adaptive learning techniques to improve reliability and generalization in different geological environments. These gaps are the core focus of the current study titled Predictive Estimation of TBM Torque and Thrust in Tunnel Stability in Challenging Environments, as the aim of the current study is to develop a complete, interpretable, and operationally useful model of prediction to enhance the safety of excavations, efficiency, and long-term performance of the tunnel in harsh environments. The present study directly bridges the gap by correlating the torque-thrust envelopes with displacement-based stability criteria. For hydromechanical coupling, the groundwater head is incorporated as a parametric variable, demonstrating its quantitative influence on the required torque-thrust capacity. Generalization across diameter ranges, existing models are typically calibrated for specific diameter ranges in project-specific geological settings.

3. Study Specific Area Details

The location of the study is the central seismic gap. The data used to examine the different types of subsurface conditions that can influence the stability of a tunnel in the Lesser Himalayan domain was based on the geological and geotechnical data derived from the Rishikesh -Karnaprayag railway project in the state of Uttarakhand, India. The railway construction area is an area of geological diversity in the Lesser Himalaya and a mixture of lithologies like quartzites, metabastics, and carbonates that are structurally controlled by the major tectonic discontinuities, which are the Main Central Thrust (MCT) and the Main Boundary Thrust (MBT), in an area where the seismic hazard and the tectonic deformation are known to be on the rise. The geotechnical study of the subsurface area in the project site involved detailed site-specific studies, classifying various types of ground with parameters including the uniaxial compressive strength, joint orientation and spacing, and groundwater flow conditions. Some of the key risks encountered during the project route were associated with the overburden, the existence of weak shear zones, active faulting and folding, and large groundwater inflows. Such considerations play a crucial part in ensuring the performance of excavations and the behavior. With the inclusion of site-related geological and geomechanical information into the computational procedure, the predictive accuracy, on the subject of tunnel stability, is enhanced, and the power to develop tailor-made excavation regimens and to control risks linked to excavation in tectonically active Himalayan geography is conditioned.

4. Tunnel Alignment Mapping

A precise assessment of the tunnel route plays a crucial role in the stability of the excavation, the construction safety, and the effectiveness of the operation of the tunnel project. Tunnel route assessment includes an assessment of the geotechnical and geological features of the assigned TBM launch and retrieval sites, lithologic variability of the tunnel route [9], spatial variation of faults [10], and variations in overburden thickness [36]. At the entrance of the tunnel (Figure 1) (C/S 1), the necessity to stabilize the ground prior to the commencement of the excavation of the tunnel is needed to avoid damaging the surrounding surface and also allow the safe movement of TBMs. The geometric relationship of the tunnel and the TBM must be strictly controlled and preserved at the TBM retrieval site (Figure 1) (C/S 5) in order to allow the safe and efficient removal of the TBM. The interface between geologically different units, especially the units of high overburden thickness (Figure 1) (C/S 2), presents new problems in ground behavior and requires the use of special support and reinforcement schemes. The change between a high overburden thickness zone and a high overburden thickness zone with a fault (Figure 1) (C/S 3) poses the most risks of ground deformation, and as such, proactive and immediate mitigation measures should be put in place to guarantee the safety of excavation [35]. The low overburden zones (Figure 1) (C/S 4) are unstable on the surface and have a possibility of collapse and necessitate constant monitoring, and quick response strategies during tunneling (Figure 1). Systematic recognition and categorization of these critical sections will allow creating site-specific excavation and support schemes and minimize the risks of geotechnology, as well as improve the success and stability of the tunnel project.

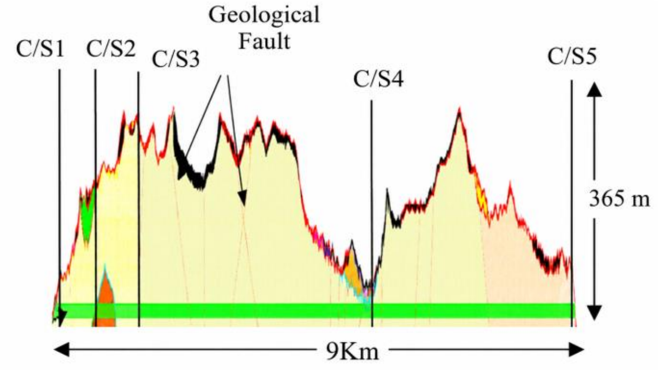

Fig. 1 Planning of the chosen tunnel position and mapping critical sections.

5. TBM Selection

To select a suitable Tunnel Boring Machine (TBM) in intricate tunneling projects, a series of parameters of a project are considered, such as the behavior of rock mass, hydrogeological, and site-specific excavation issues [37-39]. The first three TBM configurations were determined to be analyzed depending on the appropriateness to the project needs, and those are Multimode, Single Shield, and Double Shield [40, 41]. The double shield TBMs are most effective in competent and homogenous conditions. Hence, they do not usually work well in unstable or highly deformed geological environments [26, 40]. Because of the above limitations, the Double Shield configurations were not used in further tests. In a fractured or moderately competent rock formation, the Single Shield TBM was seen to perform well because of its small size. The Single Shield TBM offers more control over the progress and allows more maneuverability in rocky conditions. Multimode TBMs, on the other hand, are intended to switch between the open-mode and Earth Pressure Balance (EPB) mode. They can thus adapt to the diverse ground conditions that occur on the study alignment. The Multimode TBMs, specifically the EPB mode [24] operational feasibility, was evaluated using the Finite Element Analysis (FEA) to ascertain their ability as far as ground deformation and face stability are concerned. The FEA parametric analysis demonstrated that EPB mode becomes operationally infeasible at an accepted threshold of crown displacement (>50mm), which is constantly observed in section 3 (c/S 3) due to high overburden. These findings of the FEA showed that Multimode TBMs could not manage ground deformation and offer enough face stability to large diameter tunnels of more than 12 m.

6. Soft Computing Modelling

Analytical and numerical methods have been employed to study tunnel stress-strain response and the behavior of the crown displacement at different ground conditions [25, 43, 44]. Though initial methods of analysis gave a view on the mechanism of deformation of the tunnels, they were weak due to the capacity of representing the complexities of the heterogeneous and discontinuous rock masses with a lot of accuracy. The more advanced computational geomechanics allowed more advanced modeling frameworks to be constructed, such as the Finite Element Method (FEM), the Boundary Element Method (BEM), the Distinct Element Method (DEM), and the Finite Difference Method (FDM). These modeling frameworks have highly promoted the capability to provide a realistic simulation of tunnel-ground interaction [15, 30, 31, 33, 45]. One of the most crucial factors to consider during the choice of a suitable modeling technique is that the technique should be in line with the ground conditions and the objective of the project. Statistical methods were used in this study to screen and narrow the geotechnical input data. After the first application of the statistical methods, the Finite Element Analysis (FEA) based on Midas GTS NX software was implemented. The FEA simulations considered the soil and rock mass interactions along the periphery of the tunnel. The simulations gave estimated values of the TBM face loading and the best machine Thrust (Th) and Torque (Tq) during the different geological scenarios. Also, the FEA system allowed testing of the structural elements of the TBM, such as the cutterhead and drive system, at predicted operational loads. This process, repeated and, gave the opportunity to optimize the parameters of the excavation constantly and led to the enhancement of the efficiency of tunneling, the work of the machines, and the stability of excavation [27, 37, 42, 47]

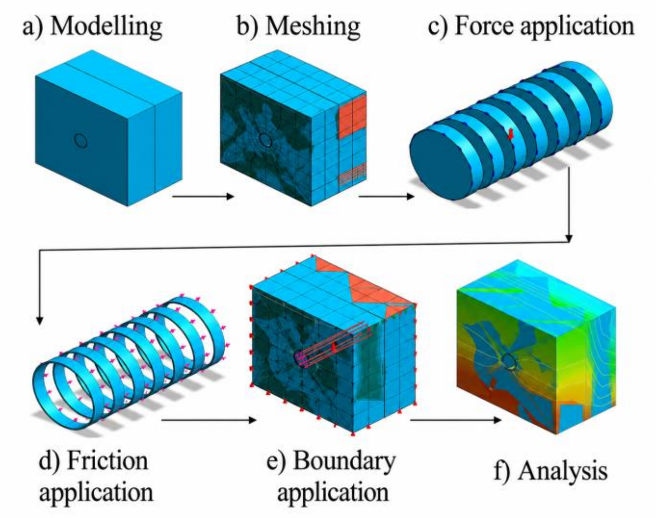

Fig. 2 Workflow of FEM application

7. Multimode TBM Assessment AT EPB Mode

In the mechanized tunneling, open-face shields, Earth Pressure Balance (EPB) Shields, and Slurry Shields, which are applicable in certain ground conditions, are widely used [38]. Multimode TBMs combine all three technologies to enable mode switching of open mode, slurry mode, and EPB mode in a single tunnel drive. This multi-purpose permits the variable functioning of the Multimode TBM under changing ground environments. Finite Element Analysis (FEA) was conducted to determine how the Multimode TBM works in EPB mode. The FEA paid special attention to some important excavation parameters, such as the face pressure, skin friction, jack thrust, and gap friction at specific positions along the tunnel alignment. The force of the face was approximated by a three-dimensional numerical model of the reaction force of the external ground. The friction between the skin was taken as 2 percent volume loss, which is equivalent to the simulated ground resistance [48]. The control of face pressure was required to ensure that the soil remained stable and groundwater was not intruded [24]. Tunnel shapes that were geometrically uniform with a diameter of 10 m, 12 m, 14 m, and 16 m were tested regarding stability by observing the movement at the crown, sidewall, and invert [22, 49, 50]. The crown displacement was the greatest, especially in folded geological regions, hence a major predictor of face stability. Segmental concrete lining (M60 grade, 400 mm thick) was a model of tunnel support [21, 22].

Figure. 3 Variation in diameter of the crown displacement at C/S1.

Sections 1, 2, 4, and 5 represented controlled displacements, thus demonstrating a possibility of TBM working (Figures 3, 4, 6, 7). Section 3, however, in a highly overburdened faulted region, had considerably high risks of deforming and collapsing the crown (Figure 5). It was not possible to stabilize Section 3 despite changes in the applied face pressure inputs, which demonstrates the limitation of Multimode TBMs to such conditions in larger diameters. These findings show that Multimode TBMs operating in EPB mode can be used in tunnels with a diameter up to 10 m, but they are not effective in the 12 m and above diameter in the examined alignment. The fact that instability is observed in greater diameters highlights the need to test Single Shield TBMs under such conditions. The significance of the equipment choice that is grounded in geology and leads to the stability of excavations and effective completion of the project is justified by this finding.

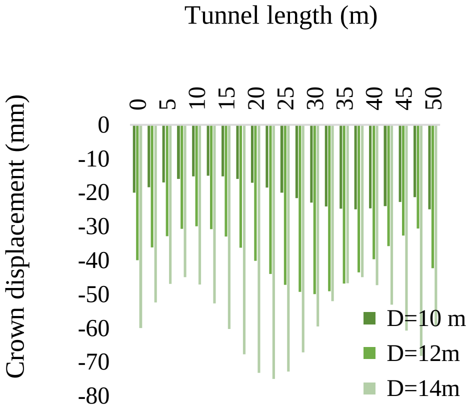

Fig. 3 Crown displacement variation by diameter at C/S1

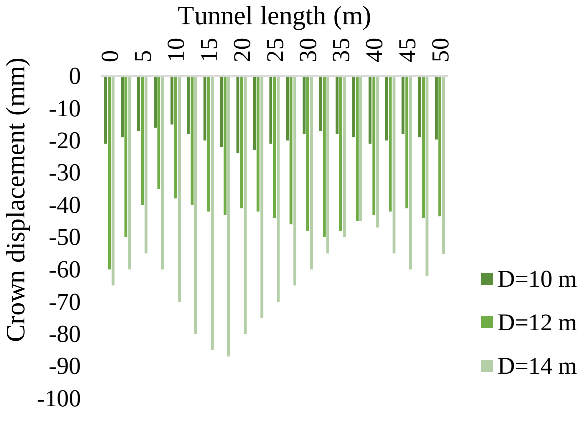

Fig. 4 Crown displacement variation by diameter at C/S 2

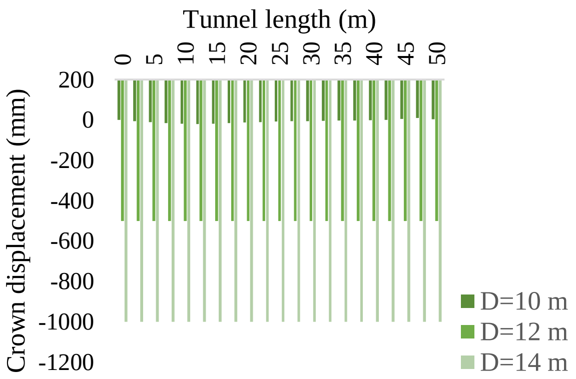

Fig. 5 Crown displacement variation by diameter at C/S 3

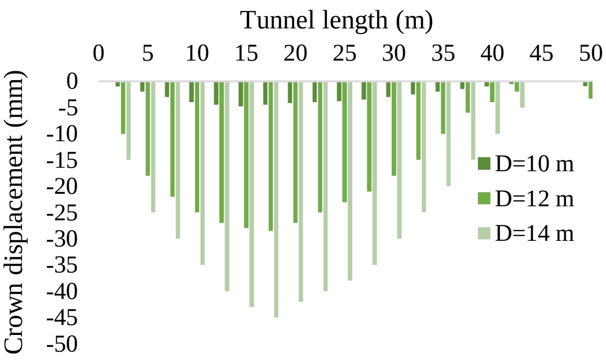

Fig. 6 Crown displacement variation by diameter at C/S 4

8. Single-Shield TBM Assessment

The section above outlined the evaluation of Multimode TBMs in EPB mode. In this section, the evaluation of Single Shield TBMs for the conditions that were studied is given. Single Shield Tunnel Boring Machines (TBMs) are ideally designed to accomplish the job of cutting through competent rock layers. Single Shield TBMs can therefore offer high performance in geologically complicated regions where stand-up time is very minimal. Stand-up time is the period of time that a tunnel face can hold itself. In mechanized tunneling, the TBM torque or rotating force needed to drive the cutterhead is a very important parameter in deciding the stability of the tunnel face and the safety of the tunneling operation in general.

A three-dimensional continuum model was developed to examine the effect of TBM torque in place of site-specific geotechnical parameters (Table 1) that took into consideration the overburden earth pressures in situ. In the first simulations, the torque and the thrust under the set conditions were estimated. The model was later further refined to incorporate hydrological effects, as will be seen in the following section.

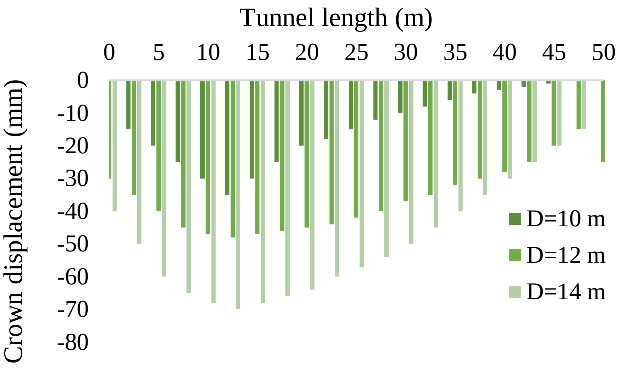

Fig. 7 Crown displacement variation by diameter at C/S 5

The research is a good demonstration of the complex interrelations between the TBM working parameters, namely, torque and thrust, and tunnel size in determining the excavation-related displacements. An analysis of the torque-displacement relationship shows that there is an incremental decrease in the crown displacement with an incremental increase in the torque in tunnels with smaller diameters (1012 m). This means that the greater torque enhances the penetration of the cutterhead as well as the sustenance of effective face pressure, which helps to enhance the stability of the excavation. Nevertheless, the trend of displacement changes at a certain point (around 15,000-18,000 kN 2 m) indicates the beginning of the ground disturbance. The point where this threshold occurs can be suggestive of circumstances in which excessive torque causes the overcutting or disturbance of the existing in-situ stresses of the weak or fractured geological material. In tunnels with greater diameters (1416 m), even rather small values of torque cause the displacement response to increase. The amplified nonmetricity of movement is mainly because of the amplified lack of support and the augmented overburden that make the tunnel vulnerable to movement. The high quadrant of the torque-diameter curve (Figure 8) is one of the areas of operation that contains too large values of displacement and reduces stability margin. This is an increased risk of face collapse, cutterhead jamming, or segmental lining failure.

Table 1. Geotechnical parameters of the tunnel alignment

Propertie	**C/S 1**	**C/S 2**	**C/S 3**	**C/S 4**	**C/S 4**
Lithology	**Metabasic**		**Quartzite**		**Dolomite**
Fault	No	Yes			No
Tectonic activity	No	Yes			No
Water inflow	Wet to dipping	Damp to dripping			Dry to damp
Overburden (m0	50	229 to 250	370	182	96
RMR	50	35			25

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<tr><td>K₀</td><td>2.5</td><td colspan="6">1.5</td></tr>
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<tr><td>Mb</td><td>4.5</td><td colspan="2">2.2</td><td colspan="2">1.6</td><td colspan="2">0.6</td></tr>
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On the same note, the thrust displacement plot (Figure 9) also exhibits a non-linear relationship. The displacement decreases linearly at low thrust values (under about 20,000 kN), which is also in line with the contribution made by controlled thrust towards supporting the tunnel face and minimizing settlements. On the other hand, for any increase in the thrust to more than 50,000 kN, the crown displacement rises at a high rate, reaching maximum values of about 90,000 -100,000 kN. This displacement behavior implies that too much thrust can lead to overstressing the face of the excavation, especially when it is heterogeneous or faulted, leading to high deformation. As observed before, the effect of the tunnel diameter on the displacement is evident, with in this case, the larger the diameter, the higher the displacement of the object in the same conditions of thrust.

The findings highlight the need to observe torque and thrust in the optimized ranges to ensure that the excavation will be stable. Non-linearity and interdependence of these parameters suggest that a small amount of deviation can lead to massive displacement increments that can be very dangerous to the overall safety and performance of the tunnels. The papers indicate that the successful prediction, monitoring, and control of the TBM thrust and the torque are critical in order to control the face stability, particularly in the large-diameter tunnels that are being excavated in intricate or tectonic regions.

The test confirms that the efficacy of mechanized subterranean tunneling tasks relies so much on the estimation and control of the torque and machine drive of the TBM. To regulate the ground deformation, in addition to the mitigation of risks to the excavation and provision of structural integrity of the tunnel during construction, optimization of torque and machine thrust is also critical. As it is suggested, the real-time geotechnical feedback should be combined with the adaptive control systems to allow informed decisions and enhance the reliability of TBM performance in a broad spectrum of geological conditions. Besides measuring the performance of TBM after undergoing hydrostatic pressure and earth pressure of the overburden, the Finite Element Analysis (FEA) of all water levels 2.5 m above the tunnel crown between 0 m and 15 m was performed to ensure that the excavation would be stable (Figure 10)

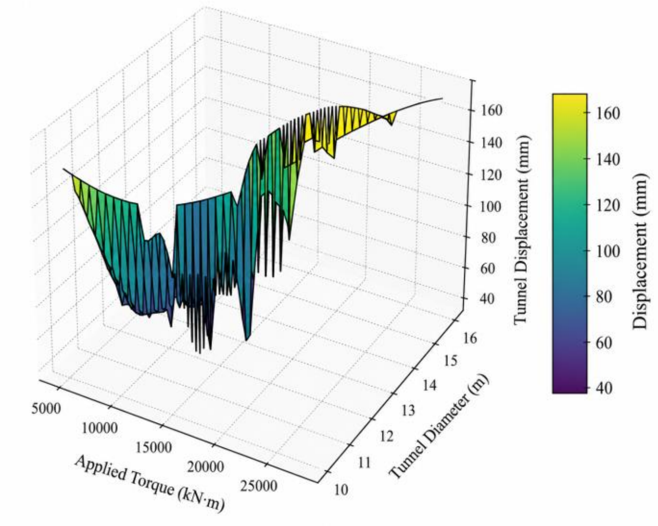

Fig. 8 Tunnel displacement VS torque and diameter

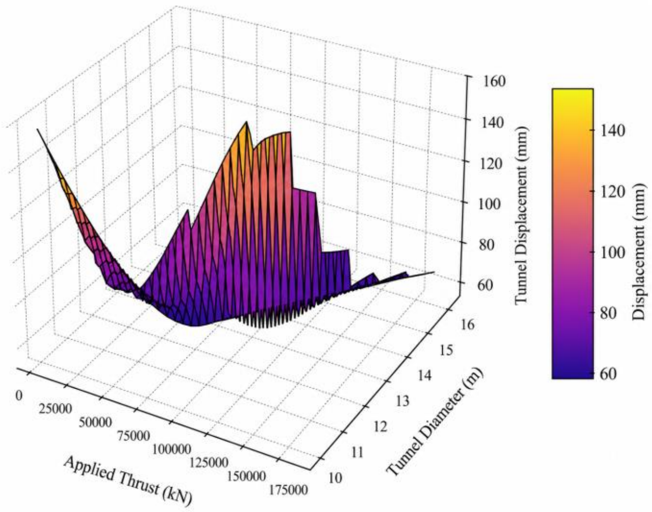

Fig. 9 Tunnel displacement VS thrust and diameter

Comparison with existing literature confirms the physical acceptability of these findings. Ates et al. [23] reported a similar nonlinear relationship of torque-thrust with tunnel diameter for the Turkish tunnel project. Zhang et al. [67, 68] analytically demonstrated the cutterhead loads scale non-linearity with cross-sectional area. The identified operational threshold in this study corresponds to the boundary of the stable operating envelope, consistent with the critical stability bounds reported by Samadi and Hassanpour [69] for geological settings. The present study advances beyond these prior works by correlating the torque-thrust threshold with displacement-based instability and by incorporating the hydromechanical effect.

9. Hydrological Consideration

Groundwater head plays a vital role in dictating the deformation response of tunnels constructed in saturated or partially saturated geological formations. As the water head increases above the tunnel crown, the corresponding rise in pore-water pressure contributes additional hydrostatic stress on the lining, causing redistribution of principal stresses around the excavation boundary [52, 53]. This pressure intensifies compressive loading at the crown and induces upward reaction at the invert, while simultaneously weakening lateral confinement of the sidewalls. Such hydromechanical interactions typically manifest as pronounced crown settlement, invert heave, and inward wall deformation, all of which collectively diminish the safety margin against instability and may escalate operational challenges such as cutterhead clogging or shield entrapment.

To quantify these effects in the context of mega-diameter tunnelling, a parametric finite element investigation was performed, extending the previously analyzed scenario governed solely by earth pressure. In this extended analysis, the groundwater head above the tunnel crown was incrementally increased from 2.5 m to 15 m, thereby simulating progressive hydraulic loading under different hydrogeological regimes. The objective was not only to evaluate the deformation trends and stress variations but also to verify whether the previously deduced TBM operational parameters, namely cutterhead Torque (Tq) and Thrust (Th), remain adequate for safe tunnelling when water-driven pressure increments are considered. The deformation profiles clearly showed that with rising head pressure, the tunnel cross-section experienced greater distortion (Figure 10).

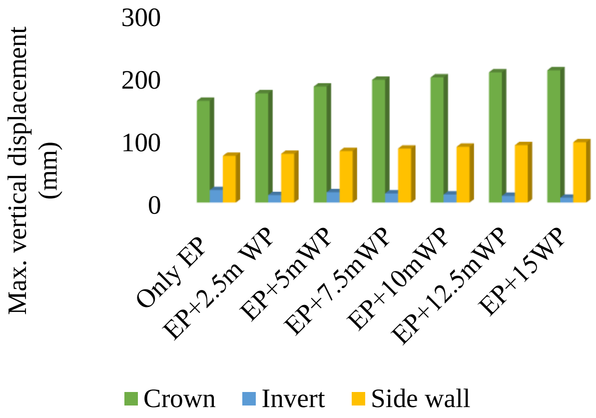

Fig. 10 Tunnel behavior under hydrological conditions

The crown exhibited intensified downward movement due to added vertical load induced by hydrostatic thrust, whereas the invert responded with measurable uplift as the internal pressure gradients reversed local stress states. Sidewalls were observed to laterally converge, indicating a reduction in ground support stiffness and a higher tendency toward squeezing behavior. Compared to the results derived under earth pressure loading alone, the cumulative impact of combined earth and water pressures significantly amplified strain magnitudes across all critical monitoring points (Figures 11, 12).

Stress contour plots further revealed concentration zones shifting toward the tunnel shoulders and crown under higher hydraulic loads. These zones signify critical regions where bending of the lining increases, raising the likelihood of segment cracking, bolt overstressing, or gasket detachment if unmitigated. As a result, the structural lining must be designed to withstand compounded stresses, particularly during advancement through pressurized aquifer zones or permeable strata.

This cumulative evidence confirms that groundwater loading serves as a dominant secondary destabilizing factor in tunnel excavation. As water pressure increases, the adequacy of the predicted torque-thrust envelope must be continuously evaluated to ensure the TBM maintains sufficient reaction capacity to counteract ground squeezing, prevent uncontrolled deformation, and sustain required face support pressure. Hence, adaptive operational strategies, such as real-time thrust adjustments, grouting-based seepage control, drain holes, and enhanced annular gap pressure regulation, are essential for the preservation of structural integrity and excavation safety in such hydro-sensitive environments.

These outcomes reinforce that hydrostatic loading is a decisive factor influencing deformation behavior and overall stability during TBM-driven excavation. The parametric results demonstrate a direct and escalating relationship between increasing groundwater head and the magnitude of structural distortion, with distinct deformation responses observed at the crown, invert, and sidewalls as the hydraulic pressure intensifies.

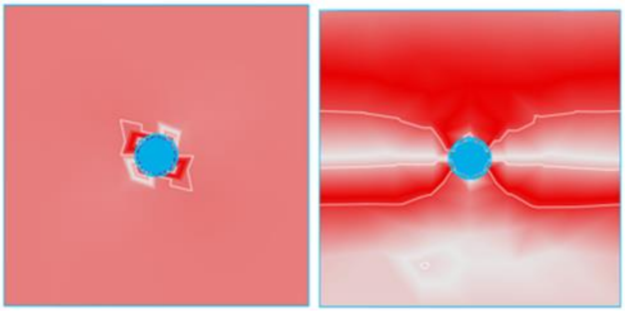

Fig. 11 Displacement and stress contour under EP

The deformation analysis indicates that the tunnel undergoes a measurable distortion pattern under elevated hydrostatic conditions. Crown settlement intensifies significantly, with reductions ranging approximately from 8% to 30%, while the invert simultaneously experiences upward heave in the order of 6% to 25%. The sidewalls also exhibit a tendency to converge laterally, indicating progressive degradation in confining ground stiffness. These deformation modes are jointly driven by excavation-induced stress redistribution and the superimposed hydraulic forces, reaffirming the prominent role of water pressure in governing structural stability during TBM-driven excavation.

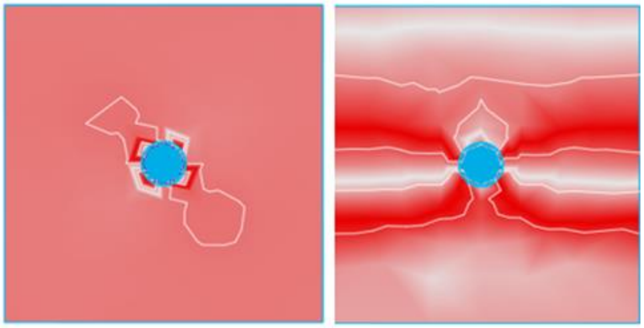

Fig. 12 Displacement and stress contour under EP with WP

Furthermore, the sensitivity of deformation is strongly controlled by both geometric and hydrogeological parameters, especially tunnel diameter and water head. Larger cross-section tunnels demonstrate comparatively lower deformation increments under elevated head pressure of 10 m, the maximum permissible torque before crown settlement exceeds 50 mm, which was reduced by approximately 15% compared to the dry condition, and the maximum safe thrust was reduced by approximately 20%. The increased stiffness and arching capability provide greater resistance to external loading. In contrast, reduced-diameter tunnels exhibit amplified displacement responses, making them more vulnerable to instability when subjected to high groundwater gradients. These observations underscore the critical need for site-specific optimization of lining design, support systems, and hydraulic control provisions to counteract water-induced deformation effects. Incorporating robust reinforcement strategies and active pressure management is therefore essential to maintain structural integrity, minimize serviceability issues, and ensure long-term operational performance of underground infrastructure

10. Interpretation and Discussion

This research project was meant to determine the variation of the mechanical properties of the Tunnels Boring Machines (TBMs) with the diameter of a tunnel and the varying types of geological conditions they are exposed to, in the context of the weaker rock mass conditions and high pressure of groundwater that is mostly linked to the Himalayas. The correlation of cutter head torque, machine thrust, and tunnel size has produced a new technique for determining whether or not a given type of TBM can be used in certain conditions that have occurred in the process of tunnelling.

The study can clearly estimate that there are variations in the excavation requirements and the behavior of the ground with the change in the tunnel dimension. To illustrate, small- to medium-sized tunnels with a diameter of up to about 10 m., multimodal, EPB-type TBMs have the ability to operate with a very satisfactory operating efficiency and low ground movements even in the scenario of variable or mixed face profiles. The study examined the movements of the ground at this size of the tunnels, and we found that they are of acceptable magnitude and that the increment in the mechanical demands with the diameter of the tunnel is uniform and foreseeable. Thus, it seems that the pressure of the face and stabilization of excavations under such conditions can be managed quite easily.

However, when the diameter of tunnels becomes mega-size (i.e., larger than 12 m), an appreciable effect on deformation response is experienced. Big spans of weak rock are easy to lose their containment, particularly where there are faults, and the ground is relaxing and behaving as such. The study also observed that previous examination of the effect of water pressure on deformations showed that water pressure led to a 6-25% increase in the crown displacements and 8-30% increase in the invert heave. Under these conditions, TBMs working in EPB mode cannot successfully control the face, and the threat of local failure or entrapment of the cutter head is significantly high.

It is against this background that the study demonstrates that torque and thrust are effective mechanical measures of stability. Parametric analysis of data gathered shows that both the torque and the thrust are more likely to vary non-linearly with the tunnel diameter, and that such a series is most evident with stratified as well as transitional ground conditions.

The present study also determined that there is an efficient performance limit near a 12-m. diameter, at which we determine that the values of torque and thrust (about 12,000 kN · m and 50,000 kN, respectively) enable a reasonable trade-off between excavation production rate and mechanical loads on the machine. Diameters above this point cause the required input energy to counter ground resistance to continue to rise exponentially, meaning it is more likely to jam.

Such critical values of torque and thrust are used to give a way of determining the mechanical viability of making use of a TBM in a specific location.

It was also demonstrated that water pressure was a destabilizing force, making the rock soft and favoring inflow and redistributing stresses at the crown and invert. The effects of water pressure were hence put into consideration when the empirical models employed to predict the mechanical behavior of the machines were refined. These updated empirical models with hydromechanical loading enhance their predictive nature and are more precise when compared with field-measured data as obtained in hydrogeologic sections. These correlations confirmed across a diameter of 6-16 m. are a good resource in the process of selecting and designing appropriate TBMs to be applied at a particular site.

Thus, in general, the findings can be summarized that the viability of a TBM application in large-diameter Himalayan tunnelling is contingent on a complicated interaction among the physical characteristics of the machine, the strength behaviour of the rock the ground is made up of, and the hydromechanical properties of the material. What is more, it is becoming quite clear that TBMs will never be just selected out of catalog-based mechanical capacity diagrams; their applicability should be judged with the help of a mixed geo-mechanical/hydromechanical performance standard. As a result, effective tunnelling in these areas requires the introduction of forward planning strategies, which incorporate pre-drainage strategies, a timely support mechanism, and possibly a hybrid mode of excavation, especially in areas where the faults are high-risk.

In general terms, the paper emphasizes the need to adopt the interplay between the mechanical characteristics of a TBM and the characteristics of the ground on which it will work in evaluating its viability, which thus will enable more informed selection decisions in terms of TBM use and will also be able to match those decisions with the anticipated issues of performance. The framework shown in this research can be useful to designers and contractors by providing them with the opportunity to take a pre-emptive measure when evaluating the possibilities of instabilities and operational risks in tunnelling projects, as they traverse the sensitive geological routes in the Himalayas.

11. Conclusion

The determination of the feasibility of TBM with consideration to the relationship between cutter head torque, machine thrust, and tunnel diameter, considering the geological and hydrogeological problems of the Lesser Himalayan region, has been given in a systematic and practical manner in the current study, with a combination of empirical modelling, numerical simulation, and observation of the real-world performance.

The study results suggest that multimodal, EPB-type TBMs can efficiently perform their work in the tunnels up to a depth of about 10 m and that the ground movement can be controlled and managed. Nevertheless, excavation becomes much harder to work in as tunnels become of mega-diameter size (i.e., larger than 12 m.). Particularly, the paper found a non-linear growth in the torque and thrust demands with the growing diameter, and the fact that there exists a clear point of operation (when Tq 12,000 kN and Th 50,000 kN) above which the stability of excavation decreases. Over this limit, especially in faulted sections where overburden is great, excavations larger than approximately one-half their length are affected by strong crown settlement and invert uplift that lead to a greater risk of collapse and jamming.

Also, the research revealed that the state of groundwater is a significant factor that leads to the destabilization of the tunnel environment. The deformation of the rock is always enhanced by hydrostatic pressures, and the displacement of the crowns and invert movements grows up to 30 percent and 25 percent, respectively. In order to deal with this problem, the empirical models were revised to incorporate hydromechanical loading. With this update, the models are more predictive in estimating the performance of TBM in water-bearing zones. Developed correlations 6-16 m. Now, they represent a solid instrument of initial TBM choice and forecasting of performance and ground management strategies.

Lastly, the paper has shown that a complex decision-making process involves an evaluation of the mechanical capacity of a TBM, and an in-depth analysis of the geological and hydrological environment at a certain location, and not just the specifications of the catalogs or generic assumptions of feasibility. This requires a detailed decision-making process to ensure that the operations in the mountainous tunneling undertakings remain stable, as the behaviors of the rocks and the pressure exerted by the groundwater usually lead to uncertainty in operations.

In spite of a strong foundation of the proposed models in future research, more research is suggested to establish calibration of the highly fractured or highly squeezing rock conditions where yield behavior is predominant, and the current assumptions are not appropriate in describing the field behavior. Better numerical coupled hydromechanical simulation software and a longer series of field data will also be useful in developing such correlations, resulting in safer and more cost-effective construction of mega-diameter tunnels in difficult settings.

Selection of a suitable Tunnel Boring Machine (TBM) to use in complex tunneling operations entails consideration of several factors of a project, such as rock mass behaviour, hydrogeology, and site peculiarities of excavation [37-39]. Three TBM constructions were first chosen to be analyzed in consideration of the project requirements; they were Multimode, Single Shield, and Double Shield [40, 41]. Carbonate of the lime TBMs have been used in the case of powerful and uniform ground. Hence, they do not work effectively in geological environments that are unstable or highly deformable [26, 40]. As a result of the mentioned limitations, the Double Shield configurations were no longer involved in the further assessment. The Single Shield TBM was able to perform better in fractured or moderately competent rocks because of its small size. Single Shield TBM gives increased control over the progress and operational flexibility in rocky terrain. Comparatively, Multimode TBMs are engineered to change to an open-mode and Earth Pressure Balance (EPB) mode. They can thus adjust to the diverse ground conditions that they meet during the study alignment. The viability of Multimode TBMs, especially the EPB mode [24], was evaluated based on the Finite Element Analysis (FEA) to evaluate their ability with regard to deformation of the ground and stability of the face. According to the FEA findings, Multimode TBMs failed to manage the face deformation and offer adequate face stability to large diameter tunnels of more than 12 m.

Tunnel stress-strain responses and the behavior of the crown displacement have been studied by a variety of analytical and numerical methods in different ground conditions [25, 43, 44]. Whereas early analytical techniques gave an insight into the deformation mechanism of tunnels, they were limited due to the fact that they were not able to correctly represent the complexity of heterogeneous and discontinuous rock masses. The highly developed geomechanics allowed a greater number of more complex modeling models, such as Finite Element Method (FEM), Boundary Element Method (BEM), Distinct Element Method (DEM), and Finite Difference Method (FDM). These models have significantly increased the power to simulate tunnel-ground interaction [15, 30, 31, 33, 45] realistically.

An important aspect that has to be taken into account in the process of choosing a suitable method of modeling is the alignment of the method to the relevant ground conditions and objectives of a project. In this research, statistical methods were used to sieve and narrow down the geotechnical input data. After the first application of the statistical methods, the use of Finite Element Analysis (FEA) based on Midas GTS NX software was implemented. The FEA simulations were used to test the soil and rock mass interactions at the periphery of the tunnel.

The simulations were able to give approximations of the TBM face loading and the most optimal machine Thrust (Th) and Torque (Tq) parameters at the different geological conditions. Also, the FEA system allowed assessments of the structural elements of the TBM, the cutterhead, and the drive system, to determine how they would support the expected loads during operation. This process was repeated, which allowed the excavation parameters to keep on refining, which led to increased efficiency in tunneling, machine performance, and stability of the excavations [27, 37, 42, 47].

11.1. Discussion On Practical Implementation

The study findings have practical implications for tunnel engineers and project managers working in challenging environments, as TBM selection and torque-thrust envelopes provide quantitative criteria. It also gives a significant effect of groundwater pressure on deformation behavior, which strongly supports investing in pre-drainage measures. The identified operational thresholds can also be used to sense alerts and action for real-time monitoring and early detection of instability of tunnels.

11.2. Limitation and Future Scope

The present research was developed under specific assumptions to maintain methodological uniformity and computational stability. Each developed FEM model was treated as a homogeneous, isotropic, and continuous medium with representative mechanical parameters derived from laboratory and field observations. The hydromechanical interaction was represented through a steady hydrostatic head above the tunnel crown, neglecting transient seepage or temporal groundwater fluctuations. Despite these limitations, the research lays a strong foundation for future development of a fully coupled predictive stability model. Subsequent studies should focus on integrating time-dependent hydromechanical analyses that capture seepage flow, pore pressure evolution, and stress redistribution under transient conditions.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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