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Analysis of EPB TBM Torque Calculation and Component Assessment: A Case Study of Mashhad Metro Line 3

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Abstract: This paper presents a comprehensive analysis of EPB TBM torque calculations, focusing on the evaluation of eight torque components and conducting a sensitivity analysis for Mashhad Metro Line 3. The significance of accurate torque assessments in optimizing Tunnel Boring Machine (TBM) operations is highlighted. By examining the contributions of various torque components—such as those arising from soil resistance and frictional forces—the most influential parameters affecting overall cutterhead torque are identified. The findings provide insights into mitigation measures aimed at reducing TBM torque, ultimately enhancing operational efficiency during tunnelling projects. This research contributes to the understanding of cutterhead performance and offers practical recommendations for improving TBM operations.

Keywords: EPB TBM; cutterhead torque; soil mechanics; tunnelling efficiency; Mashhad Metro

1. Introduction

The construction of urban metro systems increasingly relies on mechanized tunneling methods, with EPB TBMs being a preferred choice due to their adaptability in soft-ground conditions (Farrokh and Lotfi, 2025). However, excessive cutterhead torque remains a critical challenge, leading to machine wear, delays, and increased costs. The increasing complexity of urban tunneling projects demands precise understanding of machine-ground interactions, particularly regarding cutterhead torque dynamics (Farrokh and Rouhani, 2022). Mashhad Metro Line 3 presents a unique case study where two parallel tunnels excavated with identical EPB TBMs exhibited markedly different torque behavior despite comparable machine specifications. The western tunnel segment, traversing coarse-grained soils, recorded cutterhead torque values approaching 10 MN-m—approximately 2.5 times higher than those observed in the fine-grained eastern section. This discrepancy, coupled with the uniformity of TBM specifications and operational protocols, provides a controlled setting to isolate the influence of ground conditions on torque generation. The unusually high torque values observed in the western tunnel segment led to reduced advance rates, increased cutter wear, and operational difficulties, thereby justifying a comprehensive analysis of torque components. The study is thus motivated not only by the torque difference itself but by its broader implications for TBM performance and the potential to optimize tunneling operations through targeted maitigation strategies.

While foundational models for torque estimation have been proposed (Zhang et al., 2016; Godinez et al., 2015; Zhou et al., 2018), most rely on theoretical assumptions or laboratory-scale simulations, limiting their applicability to field conditions. Recent studies have begun to bridge this gap by integrating machine learning and hybrid modeling approaches. Koohsari et al. (2023) demonstrated improved torque prediction by incorporating thrust force and geotechnical parameters. Hong et al. (2021) introduced a stage-based regression framework using LSTM networks to distinguish startup and steady-state torque behavior. Fu et al. (2022) developed a transfer learning model (TRLS-SVR) to

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enhance torque prediction across varying geological contexts. These studies underscore the complexity of torque behavior and the need for field-based validation to complement predictive models.

This research advances current knowledge by systematically evaluating eight torque components in EPB TBM operations using high-resolution field data from the Mashhad Metro Line 3. The consistent TBM specifications across tunnel sections allow for controlled comparison, while detailed geological and operational records enable correlation of torque fluctuations with soil properties and machine parameters. A sensitivity analysis identifies the most influential factors affecting torque demand, providing insight into the underlying mechanics of cutterhead resistance.

In addition to diagnostic insights, the study proposes targeted mitigation strategies to optimize TBM performance, including adjustments to cutterhead design, soil conditioning protocols, and control parameters. These findings contribute to a more granular understanding of torque mechanics and offer practical guidance for improving tunneling efficiency, reliability, and cost-effectiveness.

2. Project Overview: Mashhad Metro Line 3

Mashhad Metro Line 3 represents a critical infrastructure development in Iran's second-largest metropolitan area, comprising a 24-station alignment, 23.6 km route connecting Elahieh district in the northwest to Abuzar township in the southeast. (Fig. 1.).

Tunnel construction commenced in 2016 utilizing two identical Earth Pressure Balance Tunnel Boring Machines (EPB TBMs) with 9.4-meter diameters - among the largest TBMs deployed in Iran's urban tunnelling history. In the following sections, the geotechnical characteristics of the soil layers in the study area between chainage 4+700 and 5+700 for both western and eastern tunnels are explained.

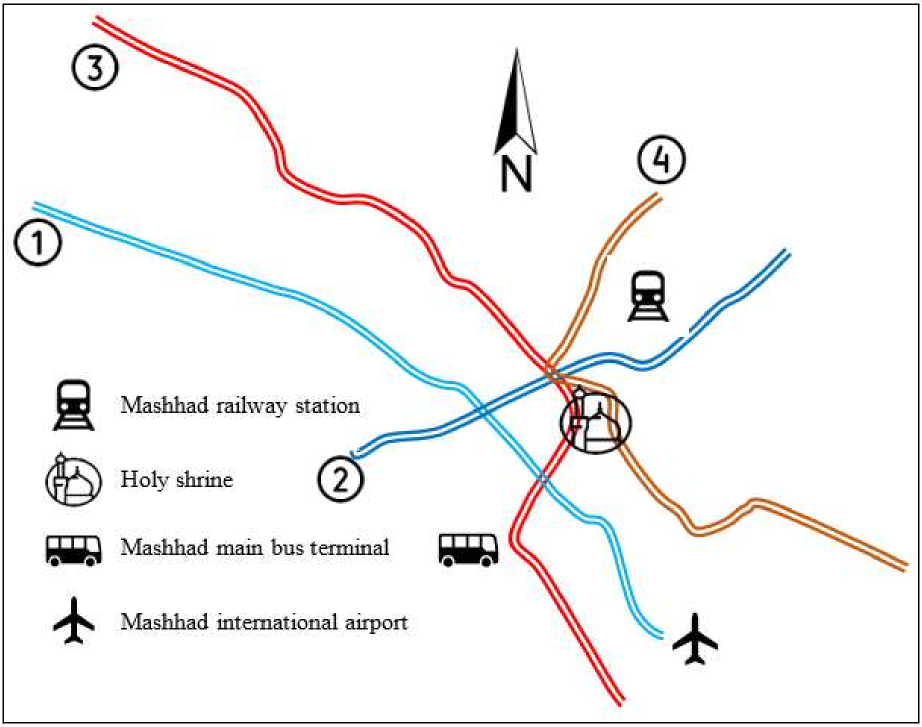

Fig. 1. Mashhad metro lines.

2.1. Western Tunnel

The western tunnel extends approximately 11,480 meters, with an overburden depth of 15–20 meters. Groundwater levels in the region range between 30–80 meters, placing the tunnel above the water table. Dominant soil unit comprises SM (Sandy Silt, often mixed with other soil types including GM (Silty Gravel). Standard Penetration Test (SPT) values are above 50 indicating very dense soil conditions. Key geotechnical properties are summarized in Table 1.

Table 1. Geotechnical data of soil units along the western tunnel route (Chainage 4700 to 5700).

Borehole	Approximate Chainage	Geological Units	Passing % (No. 200 Sieve)	Passing % (No. 4 Sieve)	Friction Angle (°)	Cohesion (kPa)
GB-31	4733	SM-GM	15-20	29-66	35	0
GB-30	5325	SM	19.1	>66	37	5
GB-29	5651	GM-SM	12.8-21.5	55-75	40	4

2.2. Eastern Tunnel

The eastern tunnel, approximately 13,800 meters long, traverses finer-grained soils with distinct geotechnical characteristics. Based on the geological cross-section, fine-grained soil units—including CL (clay) and ML (silt)—alternate with coarser-grained soils along the alignment. Toward the end of the tunnel, the proportion of CL (clayey soil) progressively increases. Key geotechnical properties are summarized in Table 2. In general, the soils encountered in the eastern tunnel are finer-grained compared to those in the western tunnel. The groundwater table is predominantly situated below the tunnel invert.

Table 2. Geotechnical data of soil units along the eastern tunnel route.

Borehole	Approximate Chainage	Geological Units	Passing % (No. 200 Sieve)	Passing % (No. 4 Sieve)	Friction Angle (°)	Cohesion (kPa)
QB-85	6048	ML-CL	>75	100	15-18	20-40
QB-86	5994	CL	>57	100	-	-
QT-87	5960	ML	>56	100	-	-

3. Analysis of cutterhead torque components based on operational data

In estimating the cutterhead torque (T) of EPB and Slurry TBMs under face pressure, eight key components are typically considered (Table 3 and Eq. 1).

Table 3. Cutterhead Torque Components.

Torque Component	Description
T1	Torque required for soil excavation
T2	Frictional torque on the cutterhead’s front face
T3	Frictional torque on the cutterhead’s rear face
T4	Frictional torque on the cutterhead’s peripheral surface
T5	Reactive torque from cutterhead structure rotation
T6	Torque due to soil shear resistance against cutterhead openings
T7	Torque from mixing rods and cutterhead pedestals
T8	Frictional torque from the main bearing seal system

$$T = \sum_{1}^{8} T_i \quad (1)$$

Fig. 2 presents an example of the torque calculation methodology for the cutterhead.

T1: Cutting torque			
R	4.6	m	*tunnel radius*
p	0.013	m/rev	*max penetration depth*
qu	1	MPa	*The compressive strength of soil*
Fc	9811	kN	*Net cutting force*
μ	0.1		*friction coef*
Tt	2306	kNm	*Torque at the tip of the cutting tools*
Tc	138	kNm	*crushing torque*
T1	**2443.1**	kNm	*Cutting torque*
T2: Cutterhead front face friction torque within the slurry or earth mud			
R	4.6	m	*tunnel radius*
A	66.5	m^2	*tunnel area*
n	0.33		*opening ratio*
Ps	207	kPa	*effective horizontal earth pressure at cutterhead center*
T2	**2827.3**	kNm	*Resisting torque from earth mud in front of TBM*
T3: Friction torque from cutterhead reverse side			
T3	**1414**	kNm	
T4: Circumferencial Torque			
R	4.6	m	*tunnel radius*
W	0.7	m	*Cutterhead width*
μ	0.1		*friction coef btw soil and steel*
Pr	207	kPa	*average effective radial pressure*
T4	**1925.5**	kNm	*Circumferencial Torque*
T5: main bearing rotation counter torque of cutterhead dead weight			
G	1350.0	kN	*cutterhead dead weight*
R1	1.4	kN/m	*main bearing rolling radius*
μg	0.004		*coefficient of rolling friction*
Pt	8802	kN	*axial load*
T5	**57**	kNm	*Resisting torque of main bearing sealing*
T6: resisting torque across the cutterhead openings			
R	4.6	m	
Ʈ	20.7	kPa	*Muck shear strength*
A	66.5	m2	*CH area*
n	0.33		*opening ratio*
T6	**1393**	kNm	*resisting torque across the cutterhead openings*
T7: The torque required to rotate the mixing bars and cutterhead frame pedestals (struts)			
Rb	2.6	m	*the distances btw the mixing bar and shield centerline*
Rp	1.4	m	*the distances btw pedestal and shield centerline*
Db	0.1	m	*the transverse dimensions of mixing bar*
Dp	0.5	m	*the transverse dimensions of pedestal*
Lb	0.5	m	*bar length*
Lp	0.9	m	*pedestal's length*
nb	4.0		*number of bar*
np	4.0		*number of pedestals*
μ1	0.15		*friction coefficient between the bars/pedestals and muck*
s'	167	kPa	*Effective face support pressure*
T7	**520**	kNm	*The torque required to rotate the mixing bars and cutterhead frame pedestals (struts)*
T8: Sealing device friction torque			
μm	0.2		*friction coefficient between sealing and steel*
Fm	1.5	kPa	*sealing pressing force*
ni	7.0		*Seal number*
Ri	1.1		*Sealing installation radius*
T8	**16**		
Total			
T	**10595**	kNm	*Sum*

Fig. 2. Cutterhead torque calculation considering component breakdown.

T1 (excavation torque) is typically calculated based on the effort required to overcome the soil's unconfined compressive strength (q_u), as illustrated in Fig. 3. This component generally results in a relatively low torque value. However, another contributor to the excavation torque—often overlooked—is the frictional force (Ff) acting on the tip surface of the cutters. This additional torque is referred to as Tt in this paper, also depicted in Fig. 3.

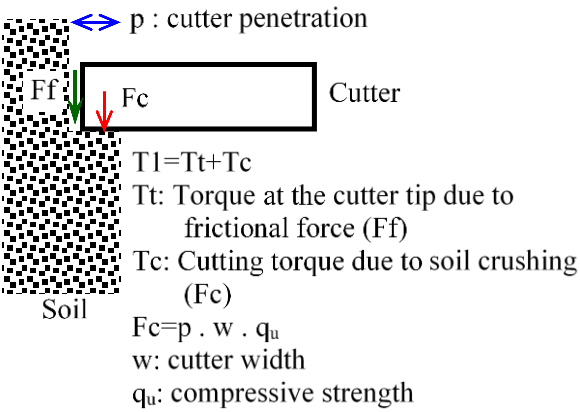

Fig. 3. Schematic of excavation force calculation for the evaluation of excavation torque.

The study of relationship between cutterhead torque and machine thrust force shows, there is a direct correlation between these two parameters (Fig. 4). Part of this direct correlation stems from frictional interaction between cutting tools' front face and high-friction tunnel face - a factor often overlooked in conventional torque estimation models. To account for this effect, the net thrust force applied to the cutting tools must first be calculated. Subsequently, the torque transferred from the cutting tools to the cutterhead can be determined by applying an appropriate dynamic friction coefficient.

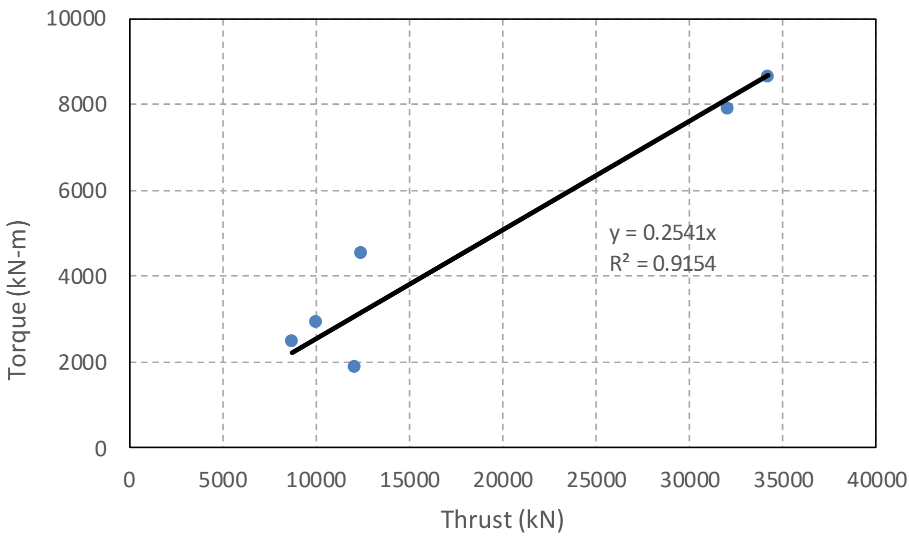

Fig. 4. Thrust-torque relationship in Mahhad metro line 3.

The surface friction torque components (T2, T3, T4, T6) are functions of both the normal pressure acting on the cutterhead surfaces and the soil-steel interface friction coefficient. While the granular soils encountered in Mashhad Line 3 would normally exhibit high friction coefficients, soil conditioning with foam additives may substantially lower these values. Quantitative data on this reduction effect remains limited. Regarding the friction coefficients between soil and steel or soil and soil, in a study conducted by Godinez et al. (2015) to calculate the dynamic friction coefficient, they concluded that the dynamic friction coefficient can be obtained from the following equation:

$$\mu = tan(\alpha\varphi') \qquad (2)$$

where:

μ: Dynamic friction coefficient between conditioned soil and the cutterhead surfaces,

φ': Effective internal friction angle of the in-situ soil

α: Correction factor to consider the shape of the surfaces in contact with the soil and the effect of soil conditioning

Based on the results of the studies by Godinez et al. (2015), the correction factor for clay, silt, and sandy soils is 0.15, 0.15, and 0.35, respectively. The internal friction angles for the soils in the tunnel studied by Godinez et al. (2015) were 33, 37, and 39 degrees, respectively, hence the dynamic friction coefficient for these three soil types was obtained as 0.087, 0.097, and 0.2, respectively. The clay and silty soil in the project studied by Godinez et al. (2015) have friction angles and adhesion values similar to the sandy and gravelly soils of Line 3 of the Mashhad Metro tunnels. Hence, the correction factor of 0.1 is considered suitable for the dynamic friction coefficient between the soil and the cutterhead surfaces in the Mashhad Metro Line 3 project.

Table 4 presents the calculated torque components and their percentage distributions (Fig. 5) for cutterheads in both eastern and western tunnel sections near the tunnel faces (chainage 4800 in the western tunnel and chainage 8000 in the eastern tunnel), along with an in-situ cutterhead rotation test conducted in the western tunnel. One note to consider is that the center cutterhead face pressure was used to calculate the torque components.

Table 4. Calculated Cutterhead Torque Components for Western & Eastern Tunnels.

Parameter	Western Tunnel		Eastern Tunnel				Rotation Test (Western Tunnel)	Avg. Rotation Test (%)	Avg. Western Tunnel (%)	Avg. Eastern Tunnel (%)
Face Pressure (bar)	1.31	1.3	0.28	0.278	0.27	0.265	0.5	-	-	-
Thrust Force (kN)	34174	32085	8756	10054	12095	12457	-	-	-	-
Torque (kN-m)	8662	7903	2489	2943	1882	4523	2000	-	-	-
Net Thrust (kN)	11973	10023	4369	5667	1125	8094	0	-	-	-
Penetration Rate (mm/rev)	16.9	17.5	16.7	17.32	17	17	0	-	-	-
T1	2993	2541	1203	1515	444	1499	0	0	33	47
T2	1736	1723	368	368	358	351	663	31	21	16
T3	868	861	184	184	179	176	331	16	10	8
T4	1567	1555	332	332	323	317	598	28	19	15
T5	39	39	14	14	14	14	19	1	0	1
T6	935	928	198	198	193	189	357	17	11	9
T7	390	387	83	83	80	79	149	7	5	4
T8	16	16	16	16	16	16	16	1	0	1
Total Torque (Tt) (kN-m)	8543	8048	2399	2711	1607	2640	2133	100	100	100
Deviation from Actual (%)	1	2	4	8	15	42	7	-	-	-

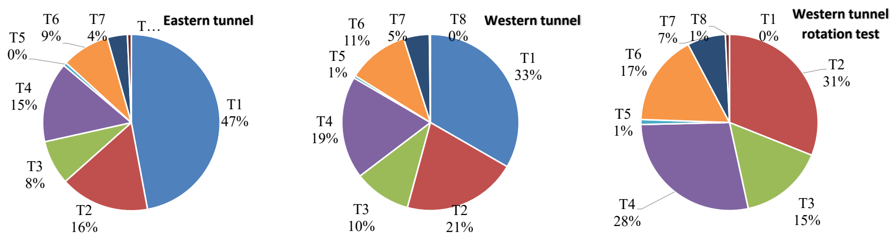

Fig. 5. Percentage distribution of the values of the cutterhead torque components in the eastern and western tunnels.

A comparative analysis of cutterhead torque in the eastern and western tunnels (Table 4 and Fig. 5) reveals:

- The western tunnel exhibits approximately 1 bar higher face pressure than the eastern tunnel (1–1.3 bar vs. 0.3 bar), resulting in increased thrust force requirements (29000–35000 kN vs. 8500–12500 kN).
- Even when comparing net thrust forces, the western tunnel requires significantly higher values. This is attributed to the presence of coarser-grained and more compact soils in the western alignment, which demand greater thrust to facilitate tool penetration and shield dragging.
- Torque-to-Thrust Ratio: 0.25–0.3 (Western) vs. 0.16–0.36 (Eastern).
- Dominant Torque Sources:
  - Excavation tools (T1 : 30–60% of total torque).
  - Friction on cutterhead surfaces (T2, T3, T4 : 40–75%).

4. Methodology

To evaluate the influence of cutterhead torque components on total torque, a sensitivity analysis was conducted. The baseline parameters in Table 5 are derived from average values observed in the western tunnel, with consideration given to adjustable parameters in cutterhead design.

Fig. 6 illustrates the percentage variation in cutterhead torque relative to the baseline under different sensitivity scenarios.

Table 5. Baseline Parameters for Sensitivity Analysis.

Parameter	Baseline Value
Face Pressure (bar)	1.3
Contact Force (Net Thrust Force) (kN)	11,000
Penetration Rate (mm/rev)	17
Friction Coefficient (μ)	0.1
Cutterhead Opening Ratio (%)	35

Key findings from sensitivity analysis are as follows:

- Most Influential Parameters (Descending Order):
  - Friction Coefficient (μ) – Highest impact on torque variation
  - Face Pressure – Directly affects frictional resistance
  - Net Thrust Force – Influences cutting and muck flow
  - Penetration Rate – Moderate effect due to soil-tool interaction
  - Cutterhead Opening Ratio – Least impact (but affects muck flow efficiency)
- Practical Implications:

− Reducing μ (e.g., via foam conditioning) significantly lowers torque.
− Optimizing face pressure minimizes unnecessary frictional losses.
− Higher opening ratios marginally improve performance but are less critical.

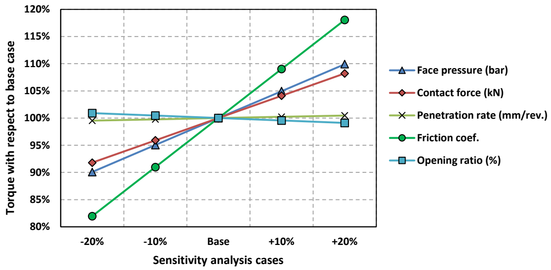

Fig. 6. Sensitivity analysis of the parameters of the cutterhead torque components.

5. Discussion

The analysis confirms that dynamic friction (μ) and face pressure dominate torque fluctuations, while mechanical parameters (thrust, penetration rate) play secondary roles. This aligns with empirical observations in EPB tunneling, where soil-conditioning efficacy directly governs torque demands. For this reason, to optimize the operation and to reduce the total torque it is recommended to prioritize friction reduction (e.g., enhanced foam injection) for torque control. To reduce the coefficient of friction between the surfaces of the cutterhead and the excavated soil mixed with foam, the following can be considered:

- Optimizing the foam injection parameters (type of foam or injection material, FIR, FER, percentage of foam concentration, arrangement of foam injection points in front of the cutterhead and near its periphery and inside the chamber, ...)
- Using coatings on the cutterhead surfaces with a lower coefficient of friction and less likelihood of adhesion.
- Using water jets in places where the likelihood of material accumulation is higher (center of the cutterhead and center of the chamber and the entrance to the screw conveyor)
- Lowering face pressure can reduce the total cutterhead torque. Adjustments to face pressure are evaluated against geotechnical stability criteria using limit state analyses. Both ultimate and service limit states should be considered to ensure that reductions in face pressure would not compromise tunnel face stability or induce ground settlement. The proposed torque reduction strategies involving face pressure optimization are contingent upon satisfying these safety thresholds and are intended to be implemented within the permissible range defined by geotechnical design standards.
- Increasing the percentage of cutterhead opening can facilitate the muck flow, reduce clogging, and lower total torque. In addition, increasing the opening area reduces the frictional forces applied to the cutterhead. Some of these factors are included in the torque calculation formulas and some are not. For example, reducing the effect of mud clogging leads to better performance of the cutting tool, the effect of which is not considered in the torque components.

Although the variation in soil composition between the eastern and western tunnel segments is a primary factor influencing cutterhead torque, other elements such as tunnel alignment, cutterhead geometry, and operational parameters also contribute. In this study, the uniformity of TBM specifications and cutting tools across both segments allowed for a controlled comparison. Operational parameters—including thrust force, penetration rate, and face pressure—were integrated into the torque component calculations and sensitivity analysis. These factors were monitored and found to be consistent, supporting the conclusion that soil contrast is the dominant driver of torque variation, while operational conditions modulate its magnitude.

6. Conclusion

The comprehensive analysis of cutterhead torque components in Mashhad Metro Line 3's eastern and western tunnels has yielded valuable insights into TBM performance across varying geotechnical conditions. Excavation torque (T1) emerged as the dominant component, accounting for 30–60% of total torque demand—particularly in the coarse, denser soils of the western tunnel. Frictional torques (T2–T4) collectively contributed 40–75%, with their magnitude strongly influenced by soil-steel friction coefficients and face pressure.

A clear linear correlation was observed between thrust force and torque, with the western tunnel requiring approximately 2.5 times higher thrust than the eastern alignment. This disparity was primarily driven by differences in soil composition and elevated face pressures. Sensitivity analysis identified friction coefficient and face pressure as the most influential parameters, with torque reductions of up to 20% achievable through targeted optimization. Recommended strategies include enhanced soil conditioning protocols, cutterhead design improvements to facilitate muck flow, and continuous monitoring of operational parameters to balance performance and tool wear.

While the study focuses on a 1 km section of Mashhad Metro Line 3, the findings are broadly transferable to EPB tunneling in similar geotechnical contexts. The torque component framework and sensitivity analysis are rooted in fundamental soil-tool interaction principles, making them applicable across projects involving both coarse- and fine-grained soils. The results reaffirm that dynamic friction and face pressure are the primary drivers of torque fluctuations, with thrust and penetration rate playing secondary roles. This aligns with established EPB tunneling practices, where soil conditioning—especially foam injection—directly governs torque demand. Accordingly, the proposed mitigation strategies are not only grounded in field data but also adaptable to site-specific conditions, offering practical guidance for optimizing cutterhead performance and excavation efficiency.

Key limitations include uncertainties in friction coefficient estimation due to reliance on back-analysis, and significant torque variability stemming from geotechnical heterogeneity. These findings underscore the critical interplay between soil properties, machine parameters, and torque demand in EPB tunnelling. For Mashhad Line 3 and similar projects, prioritizing friction reduction and adaptive face pressure control will be essential for maximizing TBM efficiency. Future research should focus on deploying real-time torque monitoring systems to refine predictive models and enhance operational decision-making.

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