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Assessing the geotechnical feasibility of shallow TBM launch in India's urban landscape: a focused case study

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ABSTRACT: This study evaluates the feasibility of using shallow tunnel boring machine (TBM) launches for underground tunneling in Mumbai, focusing on adapting a standard shallow TBM launch section to the city's unique geotechnical conditions. Mumbai's soil profile, characterized by soft clays, silts, and weathered tuff, presents challenges for conventional tunneling methods, which are constrained by high costs, long construction timelines, and the need for minimal disruption in densely populated areas. With over 23.15 million people in the Mumbai metropolitan region, projected to increase by 30 million by 2050, there is a pressing need for efficient, cost-effective tunneling solutions. Conventional methods are often impractical due to space limitations and prolonged construction periods, making shallow TBM launches a promising alternative. These launches offer reduced surface disruption and faster construction. Numerical analysis is conducted to assess the structural safety and performance of shallow TBM launches in Mumbai's challenging geology, with results confirming satisfactory performance.

1 INTRODUCTION

Urban tunneling projects in rapidly developing cities such as Mumbai are increasingly relying on Tunnel Boring Machines (TBMs) for underground construction. Shallow TBM launches, where the tunnel is launched at depths less than one time the tunnel diameter, presents a unique set of challenges. These challenges primarily arise from the limited overburden, which can lead to significant ground movement, including surface settlement, deformation of surrounding infrastructure, and reduced support for the tunnel face. While traditional TBM launches generally occur at greater depths, shallow launches require specialized engineering solutions to ensure stability and minimize disruption to the surface and existing structures.

Mumbai's geological profile, characterized by a complex and highly variable combination of soft clays, silts, weathered tuff, and basalt, presents significant challenges for tunneling operations. Conventional tunneling techniques, such as shaft box construction, typically require extensive excavation and are associated with prolonged construction timelines of 18-24 months, often leading to substantial surface disruption. In contrast, the application of shallow Tunnel Boring Machine (TBM) launches offers a more efficient alternative, significantly reducing both excavation duration and surface impact. This paper investigates the feasibility of implementing shallow TBM launches in Mumbai, considering the city's diverse geotechnical conditions and outlining the necessary engineering approaches to ensure successful deployment in such a complex urban environment.

2 METHODOLOGY

2.1 Site selection: Mumbai's subsoil conditions

Mumbai was selected for this study due to its diverse and varied subsoil conditions, which present distinct challenges for Tunnel Boring Machines (TBMs), coupled with the city's rapid urbanization, making it an ideal candidate for evaluating tunneling technologies. The geological profile of the region is dominated by Deccan basalts, associated with pyroclastic and plutonic rocks from the Upper Cretaceous to Palaeogene age, forming the Sahyadri Group (Sethna, 1999). The Deccan volcanic terrain, covering nearly 500,000 km² of the Indian subcontinent, has a thickness of up to 1.6 km above mean sea level. The Deccan basalt in Mumbai is of Eocene age (Subbarao, 1988). The geology of the region also includes ultrabasic, basic, and acidic volcanic formations with intertrappean beds, agglomerates, and tuffs. Basalt flows in the area are categorized into compound (pahoehoe type), simple, and unclassified flows (Jain et al., 2011; Singh et al., 2009). These diverse geological conditions, coupled with a high-water table, result in challenging ground behavior that significantly influences TBM performance. Mumbai's dense urban environment further necessitates the use of shallow TBM launches, as they minimize surface disruption and avoid extensive excavation pits. The city's geological profile includes soft clays, silts, weathered tuff, and basalt, with significant variability across short distances.

2.2 Geotechnical conditions at the TBM launch area

A detailed geotechnical analysis was performed to assess the properties of the strata encountered during tunneling operations. Laboratory tests, field investigations, and geotechnical models were utilized to simulate ground behavior and optimize TBM performance. The table below summarizes the key geotechnical parameters, including Uniaxial Compressive Strength (UCS), Geological Strength Index (GSI), Rock Quality Designation (RQD), Modulus of Elasticity (Ei), and Rock Mass Modulus (Erm), crucial for designing and optimizing TBM operations. The Hoek-Brown failure criterion was applied to rock layers (tuff and basalt), while the Mohr-Coulomb failure model was used for soil layers

Table 1. Geotechnical Properties of Subsurface Strata at the TBM Launch Site

Geological Profile	Depth of stratum Top (m)	Unit Weight (kN/m^3)	Poisson's Ratio	TCR (%)	RQD (%)	UCS, (MPa)	GSI	Ei, (GPa)	Erm, (MPa)
Marine Clay	0	17	0.45	-	-	-	-	-	-
Grade V Tuff	5	20	0.25	30	0	1.4	22.5	0.28	14.56
Grade III to II Tuff	6.5	21	0.22	83	51	7.4	52.5	2.94	1046.22
Grade IV Tuff	11	21	0.22	33	3	1.4	28.5	0.28	20.71
Grade IV Tuff with shale	20	21	0.22	46	13	2.9	30.5	0.58	48.75
Grade V Tuff	27.5	23	0.22	48	0	1.4	27	0.28	18.88
Grade III Tuff	32	27	0.22	66	42	15	48	5.99	1625.97
Grade II Basalt	33.5	27	0.2	89	80	55.4	67	17.95	12097.0
Grade II Tuff	36.5	27	0.22	89	59	56.6	56.5	22.6	9969.29
Grade I Basalt	38	27	0.2	96	90	37.4	72	16.83	12934

The data presented in Table 1 and Figures 1 and 2 below depict the variation of critical geotechnical parameters, including UCS, RQD, and core recovery, with depth at the TBM launch site. This data is crucial for a comprehensive understanding of the subsurface conditions and plays a pivotal role in optimizing TBM design and tunneling strategies, tailored to the unique geological challenges presented by Mumbai's complex geology.

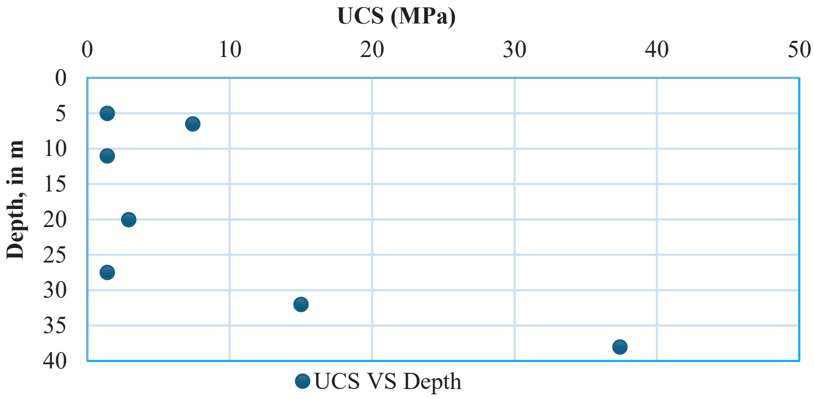

Figure 1. Variation of (Depth vs UCS)

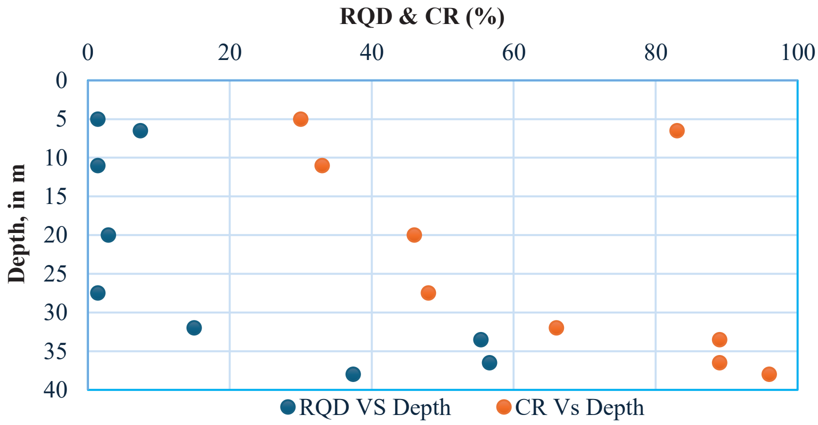

Figure 2. Variation of (Depth vs RQD & CR)

2.3 Shallow TBM launch section design for Indian geological condition

The analysis utilizes a shallow TBM launch section to assess its applicability to Indian geological conditions. The reference design includes a reinforced concrete protective slab with a thickness of 1.5 meters, a secant pile wall that is 1.0 meter thick and 7.5 meters long, with a 5-meter embedment into rock, and a tunnel with an internal diameter of 5.8 meters (outer diameter 6.35 meters). Numerical analysis was performed to evaluate the structural and geotechnical performance of this design. The system is designed to support the TBM launch while maintaining the alignment gradient until a safe geological section is reached. The protective structure includes the reinforced concrete slab, which ensures stability and prevents collapse during the TBM launch. Additionally, an unreinforced concrete slab provides temporary protection to mitigate subsidence risks during the TBM's progress, with both slabs length and specifications adjusted based on design requirements and local conditions.

A Secant pile wall serves as a temporary protective structure, stabilizing the surrounding area and preventing lateral ground movements. The wall is designed with a 5-meter embedment in rock to ensure its stability under load. For the numerical analysis, the geotechnical design parameters for the clay within the improved zone were exclusively considered. Prior to improvement, the clay exhibited a cohesion (c) of 15 kPa and a Young's Modulus (E) of 2700 kPa. Following ground treatment, these parameters were enhanced to a cohesion (c) of 50 kPa and a Young's Modulus (E) of 9000 kPa, reflecting the increased strength and stiffness achieved through the ground improvement process. These measures are critical for providing optimal steering control of TBM. The support systems, including the reinforced slab and Secant pile wall, remain in place until the TBM reaches more homogeneous material, allowing the necessary soil arching to occur above the TBM and ensuring its stability and safe passage. The Numerical model for this design is shown below.

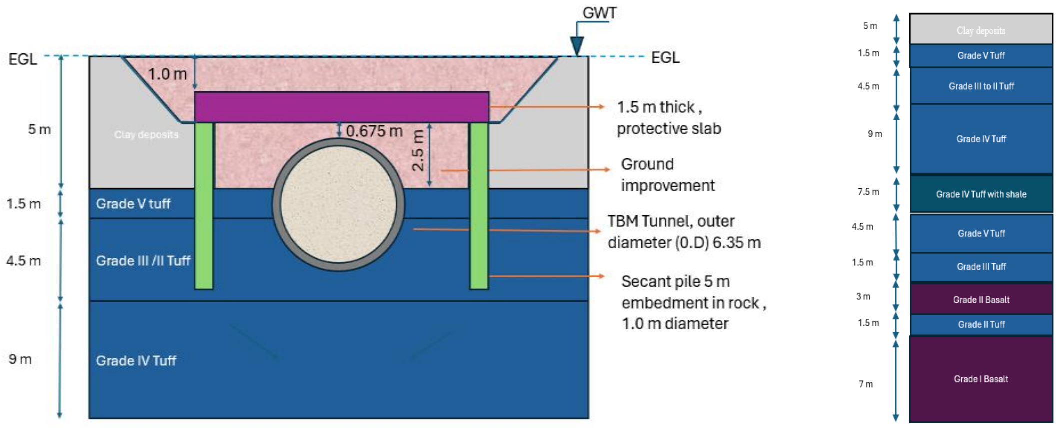

Figure 3. Cross-section utilized for numerical analysis at the shallow TBM launch

3 NUMERICAL ANALYSIS AND CONSTRUCTION METHODOLOGY

The construction of the Tunnel Boring Machine (TBM) launch site is a complex process that requires careful planning and execution to ensure safety, stability, and efficient tunneling operations. The process begins with a comprehensive initial phase, which includes site surveying, geotechnical investigations, infrastructure setup, and implementation of safety protocols. These initial steps lay the foundation for the subsequent excavation work. Excavation begins at the surface level, Initial excavation proceeds with a temporary sloped cut from the surface, reaching a design depth of 2.5 meters. Following the completion of this initial excavation, the secant pile wall is meticulously constructed, subsequently providing critical shoring and effectively stabilizing the excavated profile for the ensuing TBM launch operations.

Dewatering measures, including well-point systems, are employed to manage groundwater levels and prevent hydrostatic pressures that could destabilize the excavation site. In the next phase, ground improvement techniques such as soil replacement or stabilizing agent injection are used to enhance the clay layers up to a depth of 5 meters. A protection slab is placed to distribute loads and maintain stability during the excavation. Once these preparatory steps are complete, the TBM is prepared for launch. Tail void grout is applied to fill any gaps between the TBM and the final tunnel lining, ensuring water ingress is prevented. A contraction factor is incorporated to account for any potential conicity during TBM operation.

Once TBM is activated, continuous monitoring of ground movement, Secant pile-wall deflection, and surface settlement is conducted to ensure the stability of the TBM and surrounding infrastructure. Grout pressure at the TBM tail is closely monitored to ensure tunnel integrity and minimize void formation. After the tunneling operations are completed, a final assessment is carried out to evaluate the effectiveness of the excavation. Shear forces, bending moments, and deformations in the Secant pile wall are analyzed, and surface heaves and Secant pile wall deflection are checked to ensure they are within acceptable limits. The effectiveness of the void grouting process is also assessed to guarantee the long-term stability of the tunnel.

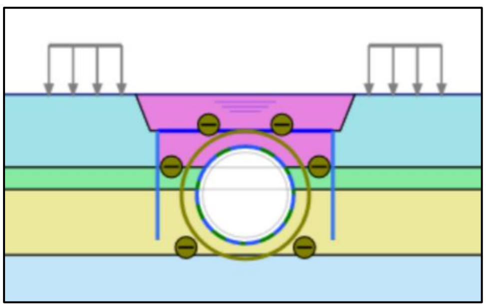

Figure 4. Numerical model at final stage after installation of tunnel lining

4. RESULTS AND DISCUSSIONS

4.1 Numerical simulation output

The analysis of the shallow TBM launch section yielded critical data on the geotechnical and structural performance of the design. Through numerical simulations, the performance of key structural elements such as the Secant pile wall and surrounding soils was assessed in detail. The results of these simulations provide insights into the behavior of the system during tunneling and the effectiveness of geotechnical measures to control surface settlement and lateral deflection.
The analysis of specific settlement characteristics reveals that surface settlements primarily occurred due to the tunneling operations.

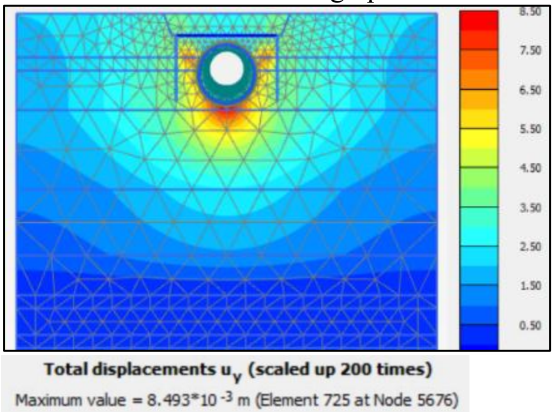

Figure 5. Deformations at final stage after installation of tunnel lining

Figure 5 shows the detailed deformations at the final face of the tunnel after the installation of the TBM lining. This figure underscores the localized effects of tunneling on surface stability.
Settlement analysis showed a maximum settlement of 9 mm, which is within the expected range for tunneling in Mumbai's soft soil conditions. This result is significant as it suggests that the shallow TBM launch design can be safely implemented in urban environments without causing excessive settlement or disruption to surface infrastructure. The uniform distribution of settlement along the alignment indicates that the system effectively minimizes localized surface displacement.

The lateral deflection of the Secant pile wall was observed to be minimal. This confirms that the Secant pile wall performs as intended under the imposed loads from the TBM. The wall provides the necessary lateral resistance, ensuring the integrity of the tunnel during excavation. The lateral deflection profile further supports the adequacy of the wall design for the specific geotechnical conditions encountered.

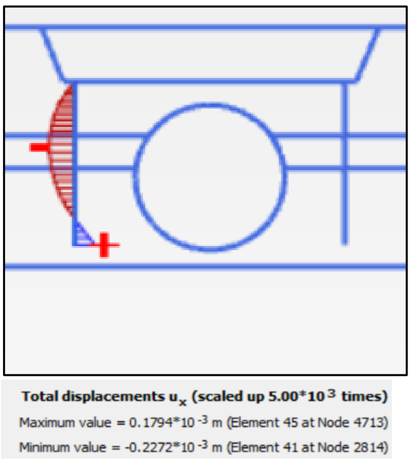

Figure 6. Deformations of secant pile wall at final stage after installation of tunnel lining

This figure illustrates the calculated lateral deflections of the Secant pile wall at the final stage of installation. This figure is integral for assessing the performance of the Secant pile-wall under dynamic loads imposed by the TBM operations.

The results suggest that while the shallow TBM launch method is effective for the given geotechnical conditions, further design optimization may be necessary. Additional geotechnical measures, such as soil improvement techniques, should be considered to reduce risks associated with localized instabilities and ensure the long-term safety of the project.

The analysis of the bending moment variation along the tunnel lining, with a maximum value of 47.94 kN/m, is crucial for assessing the tunnel's structural integrity under dynamic loads. This data helps optimize the tunnel lining design, ensuring it can withstand both construction and long-term operational conditions. Including this analysis in the paper ensures the safety, durability, and efficient use of materials in the tunnel's construction, providing confidence in its performance. throughout its service life.

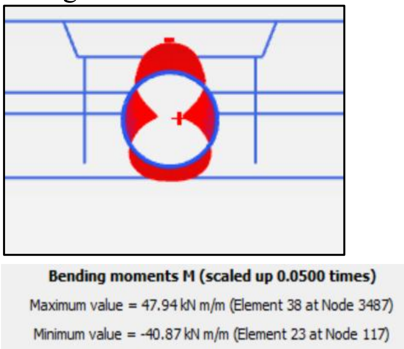

Figure 7. Bending moment distribution at the final stage of tunnel lining installation.

This figure illustrates the variation in bending moments along the tunnel lining, highlighting critical stress points that ensure the tunnel's structural integrity under operational loads.

4 CONCLUSIONS

Feasibility of Shallow TBM Launches: The feasibility of shallow TBM launches in urban environments is primarily determined by the local geological conditions. According to Numerical analysis, the expected settlement is minimal (9 mm), and the deformations of the secant pile remain within the permissible limits as outlined in the reference. This ensures that tunneling can be carried out safely, with negligible impact on adjacent structures.

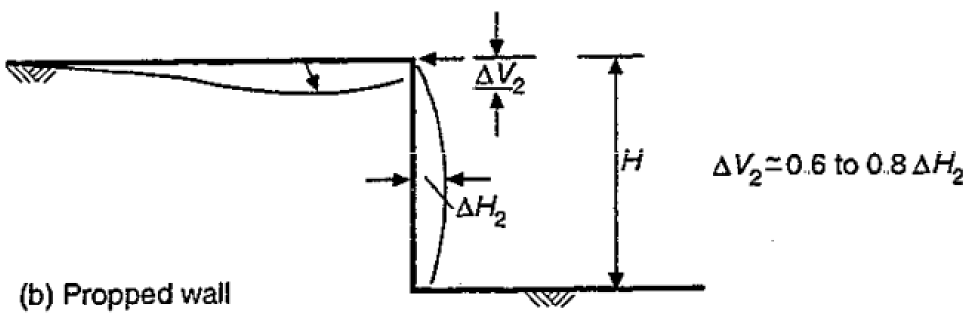

Figure 8. Comparative wall and ground movements after Burland et al. (Ciria C517)

Structural Integrity: The adopted design and construction methods effectively control ground movement and structural deflection, maintaining safety within permissible limits.

Continuous Monitoring: Real-time monitoring using advanced instrumentation (e.g., inclinometers, piezometers) is crucial for detecting and mitigating potential risks during tunneling.

Ground Improvement: Pre-excavation ground improvement techniques, such as grouting and soil stabilization, are recommended to enhance soil stability and minimize settlement and deflection risks.

Shallow TBM Launch Viability and Future Work**:** Shallow TBM technology, when implemented with comprehensive geotechnical assessments, continuous monitoring systems, and robust risk management strategies, offers significant advantages such as reduced noise pollution, a smaller carbon footprint, and minimal environmental impact. Its adaptability to various geological conditions contributes to efficient urban infrastructure development. Continued innovation in TBM methods and geotechnical practices will be crucial for enhancing safety, operational efficiency, and the overall success of underground construction in future projects.

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