Special Issue - 2021
International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
NCETER - 2021 Conference Proceedings

Performance Review of Tunnel Boring Machines

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***Abstract*— Tunnel-boring machines are the primary gear for the development of trenchless underground designing tasks, for example, rail travel, civil designing, railroad tunnels, and so on. This paper reviews various tunnel boring machine types, cutting tools, and machine performance through several case studies. It was found that these machines are highly efficient in various projects associated with hydropower, sewerage, water supply, irrigation, and transportation. The idea of the ground conditions decides the decision and situating of the unearthing apparatuses for the shaper head or the cutting wheel. Just if the apparatuses are consummately coordinated to the topography, the TBM can accomplish high tunneling exhibitions. It was also noted that the machine performance depends on the change of uniaxial compressive strength of soil in a variety of geological rock compositions and underground water reservoirs.**

Keywords*— *TBM, UCS, Tunnel, Boring.

I. INTRODUCTION

The bore construction method for tunnels involves digging a tube-like passage through the earth. This is usually applicable for mountain tunneling, tunneling under bodies of water for various purpose like transportation and other supply lines. Rather than conventional tunneling methods which extensively use explosives and manual labor, mechanized tunnel excavation is done by Tunnel Boring Machine (TBM). The cutter head on the machine rotates and thrusts into the rock surface that lies ahead of it. This thrust causes the cutting disc tools to break the rocks. The grippers/braces develop the reaction to applied thrust and torque forces with the help of anchoring. Tunneling with it is much more efficient and results in shortened completion times, assuming they operate successfully. The Double shield tunnel boring machine used in subsurface mining has been shown in Fig. 1. Drilling and blasting however remains the preferred method when working through heavily fractured and sheared rock layers. A typical TBM includes a hydraulic thrust system, and an attitude positioning system. The cutter head system undertakes the task of excavating rocks and soil, which plays an important role [1]. The technologies of the Double-O-tube (DOT) and Multi-circular Face (MF) shield machines (Fig. 2(a) and (b)) were mainly developed in Japan [2]. Compared with a parallel twin tunnel, the width of a cross-section excavated by a DOT shield machine is much narrower, to be mainly applied to the integrated excavation of subway stations. However, owing to the complex excavation cross-sections and relatively large ground disturbance soil can adhere to the TBM shield body and accumulate during TBM advancement. A quasi-rectangular TBM was developed based on the DOT shield machine by increasing the eccentric multi-shaft cutterhead in order to excavate the blind areas. The excavation cross-section, whose upper and bottom shapes are circular arcs, has an ellipse-like quasi-rectangular shape that has improved the bearing capacity of the equipment and segments, solved the soil problems and reduced ground disturbance (Fig. 2(c)).

The quality and lifetime of the excavation tools have a noticeable effect on the tunnelling performance and the economic efficiency of mechanized tunnelling. The high material quality of the tools ensures the productive removal of soil or rock on the one hand, and low downtimes due to high durability on the other. The excavation tools are installed on the cutterhead – in soft ground called cutting wheel. With the rotational movement of the cutterhead and the thrust of the hydraulic jacking stations, the excavation tools loosen the rock and / or the soil at the tunnel face. Depending on the geology, the cutterhead is equipped with cutting knives and / or disc cutters (discs) or rippers. To ensure that a project remains within the calculated budget, also with respect to tooling, the excavation tools must perform as forecast even with extremely high rock strengths, abrasion and water pressures.

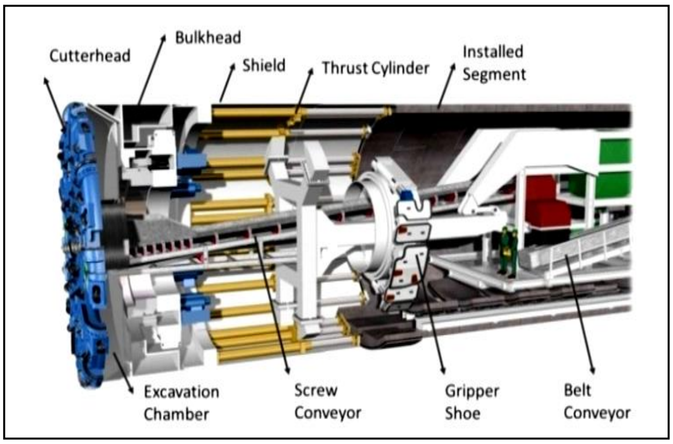

Figure 1. Double Shield Tunnel boring machine used in subsurface mining

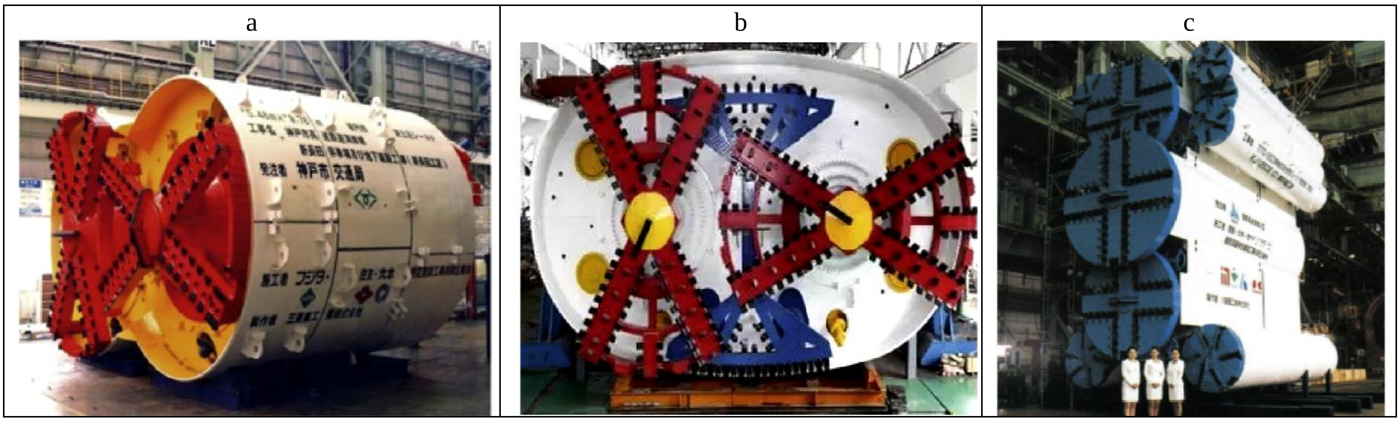

Figure 2. (a) DOT shield machine, (b) quasi-rectangular shield machinery, (c) MF shield machine

II. OPERATING PARAMETERS OF A TUNNEL BORING MACHINE

A. Parameters for selecting TBM types

Tunnel Boring Machine includes sophisticated types of equipment for excavating tunnels with the help of a variety of soil and rock strata. On average it excavates around 50-60 feet per day which is 20 hours of excavation approximately. The best machine for a project is selected on the basis of geological conditions of the site. A standard specification of double shield TBM machine is shown in Table 1 to get a fare idea of cutting parameters.

TABLE 1. SPECIFICATION OF DOUBLE SHIELD TBM [3]

Parameters	**Value**	**Parameters**	**Value**
Machine diameter	4.65 m	Cutter head power	1250 KW
Cutter diameter	432 mm	Cutter head speed	0-11 rpm
Numbers of disc cutters	31	Cutter head torque	1723 KN-m
Disc nominal spacing	90 mm	Conveyor capacity	200 m^3/hr
Maximum operating cutter head thrust	16913 KN	TBM weight	170 ns

Basically, it can be classified into eight types depending on both hard rock and soft ground. Gripper type is suitable for driving in hard rock conditions when there is no need for a final lining. Double-shield type is generally considered to be the fastest machine for hard rock tunnels. Single-shield type is used in soils that do not bear groundwater and where rock conditions are less favorable than for double shields, such as in weak fault zones. Earth pressure balance technology is suitable for digging tunnels in unstable ground such as clay, silt, sand, or gravel. Slurry is used for highly unstable and sandy soil. Mixshield technology is a variant of conventional technology for heterogeneous geologies and high-water pressure. Pipe jacking also called micro tunneling to small-scale tunneling method for installing underground pipelines with minimum surface disruption. Partial-face excavation machines have an open-face shield and can sometimes be more economical.

B. Parameters involved in the selection of Cutting Wheel and Cutter head

The nature of the ground conditions determines the choice and positioning of the excavation tools for the cutterhead or the cutting wheel. Only if the tools are perfectly matched to the geology, the TBM can achieve high tunnelling performances. However, the respective ground conditions challenge the reliability of the tools in different places. In soft soils, precautions must be taken to stop the disc cutters from getting clogged. During excavation in hard rock, such as granite, the disc cutters must pass the absolute hardness test. In addition to the geology, limited space at the cutterhead and the maximum possible load on the disc cutter bearings are also crucial factors when choosing the appropriate tool size. A wide range of cutting knives, buckets, rippers and other tools complement the spectrum for operations in loose soils. With respect to these types of tools, the durability and material composition are also key factors in optimizing time and costs. The durability of the excavation tool edges and/or teeth is improved enormously by soldering carbide metal – tungsten carbide. Depending on the geology, cutting knives, buckets and rippers are given a welded hard-facing on the tool body to protect it against abrasive soil paste. [4] The high-alloy tool steel of the cutting ring must not only be very hard to resist wear, the material toughness is also an important factor for its lifetime. Excessively brittle steel would lead to early material spalling at the cutting ring during rock bursts, which happen occasionally. Excavation tools up to 8 inches for smaller excavation diameters are also made of high-alloy tool steel. Various type of disc cutters, their operational orientation and cutter head geometries have been shown in Figure 3.

When the rotating cutting wheel on the TBM head is pushed forward against the tunnel face, cutting tools mounted on the cutter head are in contact with the ground and are thus subject to continuous wear processes. This wear behavior of the cutting tools is highly related to earth pressure or abrasiveness and machine steering parameters such as the face support pressure, advance speed and cutting wheel rotation speed. Whenever a tool reaches a critical wear level and must be replaced, the production processes of the TBM must stop in order to get access to the excavation chamber and to the cutting wheel. Unstable ground conditions require a pressurized excavation chamber to prevent a collapse of the tunnel face. Releasing the support pressure and conducting maintenance work in atmospheric pressure conditions significantly increases the risk of a tunnel face collapse and is mostly unfeasible. However, when working under pressurized conditions, additional time is needed for workers to adapt to pressurized conditions. Consequently, maintenance work is an elaborate and time-consuming process significantly decreasing the performance, but necessary in order to ensure workability of the TBM. A maintenance procedure for TBM cutting tools can be divided into the mobilization processes, inspection and tool replacing work and the demobilization processes [5]. The overall mobilization process (t_{mob}) includes lowering the level of support (t_{low}), compressing workers ($t_{compress}$), installing working platforms ($t_{installation}$) and cleaning the cutting wheel ($t_{cleaning}$).

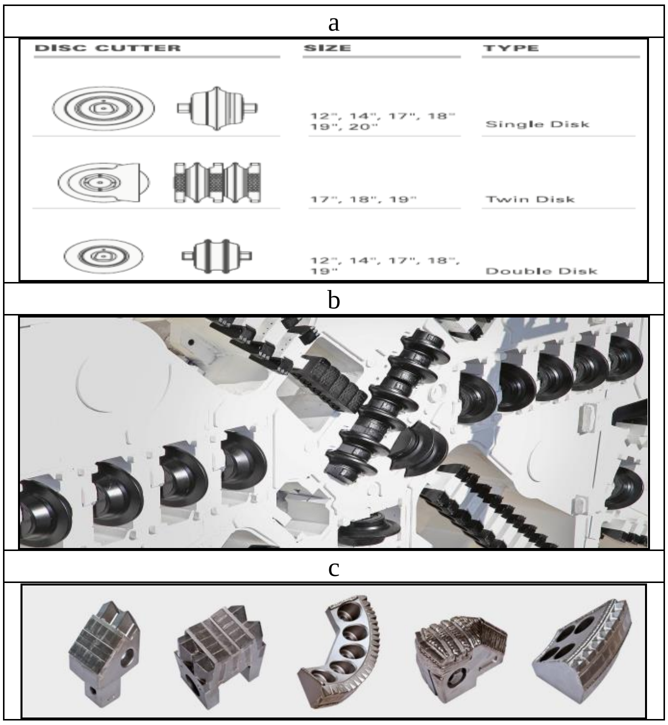

Figure 3. (a) Disc Cutter Size and types (b) Cutter Placement on TBM shield, (c) Geometry of Cutter Heads

III. CASE STUDIES ON TBM PERFORMANCE AND PARAMETRIC EFFECTS

A. Subsurface System Tunneling

Change of all surface water pipelines and to create subsurface systems by constructing tunnels to avoid problems of leakage, unconventional loss and also to protect water from contamination.[6] To improve the water supply to Vakola, a 12.24 km long tunnel between Maroshi and Ruparel College was excavated by Tunnel boring machine (Fig. 4) from Maroshi vent hole to Vakola vent hole where vertical shafts were constructed at either end. The inlet shafts of 82.0 m and 68.0 m in depth from ground level, 9.0 m in diameter [7]. The study establishes a relationship between rock mass characteristics, UCS of the Deccan trap rocks and TBM performance shown in Table 2.

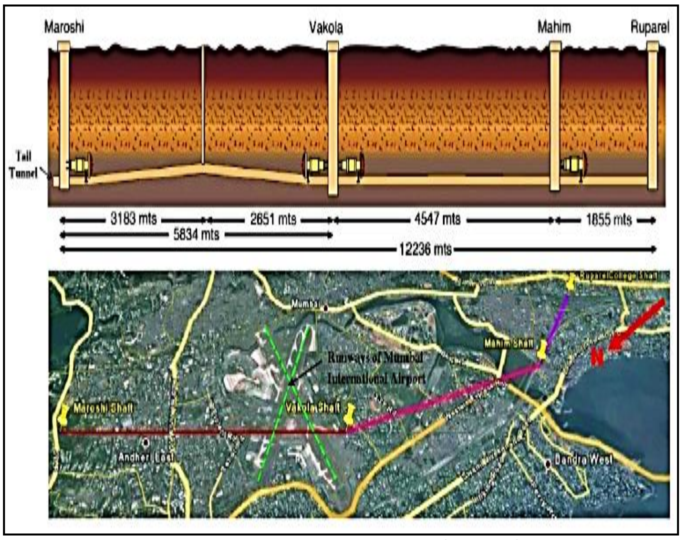

Fig 4. Longitudinal section and plan of tunnel from Maroshi to Ruparel College [7]

Studies indicate that in Deccan traps, variations in rock types, flow contacts, rock strength, and volumetric joint amount with presence of weak zones have predominantly affected the penetration rate and stability of tunnels [3]. It had been well recognized that joints or fractures have an important effect on the machine performance. On the basis of a large number of case studies, it concluded that with the decrease of joint spacing, the TBM penetration increases distinctly [8]-[10]. The maximum penetration rate was recorded for an angle of 60°. It was also noted that with the increase of joint spacing, the effect of joint orientation decreases.

TABLE 2. TBM PERFORMANCE IN MAROSHI–VENT HOLE AND VAKOLA–VENT HOLE TUNNELS. [7]

Tunnels	Tunnel boring length (m)	Shape	Excavated diameter (bore section) (m)	Finished diameter (m)	Excavation quantity (m^3/m)	Volume (totalexcavation) (m^3)
Maroshi –vent hole	3086.34	Circular	3.6	3.0	10.18	31,419
Vakola–vent hole	2590.4	Circular	3.6	3.0	10.18	26,370

Studies show that the penetration rate decreases with increase in uniaxial compressive strength. The comparison of measured penetration rate with empirical model developed by Graham, in which, the penetration rate is computed using this and average thrust per cutter, showed good agreement with coefficient of determination [11,12]. The study shows that the TBM performance was maximum in rock mass rating (RMR) range from 40 to 75, while slower penetration was recorded both in very poor and very good rock masses. It is well known that Deccan volcanic cover a vast area of nearly 500,000 km^2 of the Indian subcontinent and attain a thickness of 1.6 km above. It was widely jointed and provided stable ground condition for tunneling. Due to its structural and textural variation, the UCS of the intact basalts varied from 33.35 MPa to 143.33 MPa and the rock mass fall under fair to good rock mass categories [7]. The rock breakage process is closely related to the machine parameters, such as TBM diameter, cutter line spacing, cutter diameter, tip width, maximum RPM, total thrust and torque. The boring time cycle details with respect to international norms are given in Fig. 5. The degree of compaction and grain size also vary in top, middle and bottom portions of each flow, due to these there is no linear correlation found between RMR and TBM penetration rates.

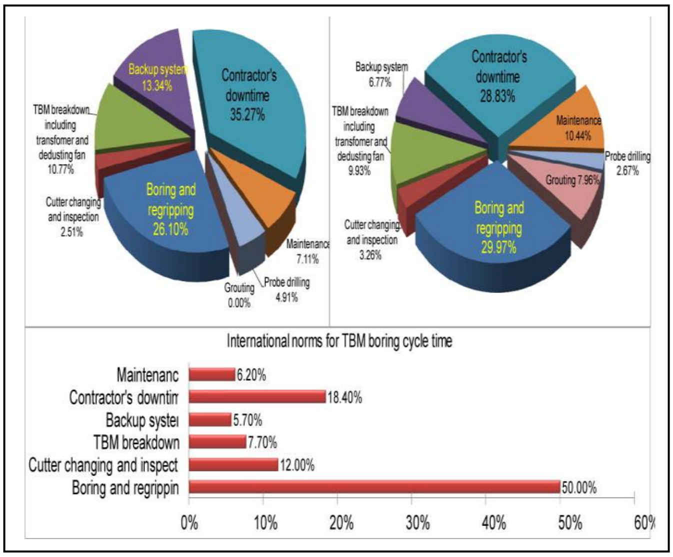

Figure 5: Boring time cycle details with respect to international norms [15]

B. Large Tunnel Excavation with TBM under-passing two highway Tunnels

It deals with the performance of Tunnel Boring Machine (TBM) opted for the construction of the Interstate Raw Water Transfer (ISRWT) project currently constructed in Selangor-Pahang, Malaysia. In this project, the 44 km Interstate Raw Water Transfer tunnel is designed to cross solid rock along the alignment with the overburden at various points. Considering the geological condition of the proposed alignment such the hard rock of Titiwangsa Main Range Granite, open type TBM was selected [13]. The evaluation on the performance of TBM is based on parameters such as boring energy, rate of penetration (ROP) and rate per minute (RPM). Three different data from tunnel site has been reported in literature, the daily tunnel mapping record, the TBM performance data and lab test results of Uniaxial Compressive Strength (UCS) on rock samples at every 50 m of the tunnel. The daily mapping recorded the strength of intact rock, joints properties and groundwater condition. The 'UCS/SHR value' was derived from the Schmidt Hammer Rebound (SHR) test while 'UCS rock core' was obtained from testing fresh rock of every 10 m cut-off in a non-discontinuity area. Three block samples (A, B & C) from the high groundwater inflow area were tested for UCS (Dry & Wet). Table 3 displays the results of Uniaxial Strength Test for dry and wet specimen respectively.

The two tests showed a satisfactory correlation as the rebound hardness values decreased with the decreasing value of UCS. It shows that the strength of rock decreased or becoming less, more than 50% from its dry value when it is wet. Few difficult excavations by the TBM were envisaged due to the existence of fault zones, high overburden and potential risk of crossing water bearing zones. In one of the locations 10 ton/min of sudden inrush warm water was experience where TBM recorded 46.50 N/mm2 of boring energy, 7.10 rev/min of RPM and 0.80 m/h of ROP. Due to these reasons slight drop of boring energy and daily progress was recorded. It was noted from reports that at specific locations high grade rock required high type of support system because the presence of sheared zone of fresh rock [14]. Boring energy was found low due to the presence of favorable fracture orientation. At some places water ingress was very high at more than 300 litre/min which weakened the rock into smaller pieces and caused higher excavation progress per day.

TABLE 3. UCS RESULT FOR DRY AND WET ROCK SPECIMENS

Dry / Wet	**Specimens**	**UCS (MPa),**	**Young's Modulus**
Dry	AD1	176.048	56.875
Wet	AW8	69.761	31.674
Dry	BD1	132.129	56.525
Wet	BW5	52.354	62.272
Dry	CD1	246.981	82.106
Wet	CW3	123.566	52.431

IV. CONCLUSION

The invention of the tunneling machine has revolutionized tunneling history indeed it had revolutionized the creation of spaces under our cities allowing metro systems, water and sewage systems, and underground cable networks, all to be built in a safe and sustainable manner. The influence of joint orientation on TBM penetration rate was widely observed. While ensuring tunneling safety, an average penetration rate of 2.10 m/h and a maximum monthly progress of 542.6 m was noted in the case studies. These types of machines have the advantages of limiting the disturbance to the surrounding ground and producing a smooth tunnel wall. This significantly reduces the cost and makes it suitable for heavily urbanized areas. The major disadvantage is the difficulties to transport and the upfront cost which reduces as the tunnel gets longer. The study provided better understanding of using TBM for tunneling projects for hydropower, sewerage, water supply, irrigation and transportation in various geological scenarios.

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