The Effect of Tunnel Diameter and Project Area on The Productivity of Tunnel Boring Machines

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ABSTRACT

There has been an increasing trend in tunnel construction for the transportation of people, goods, and liquids. In order to ensure the success of a tunneling project, it is imperative for tunneling contractors to possess adequate information regarding the scope of work, project features, and characteristics of the ground in order to calculate the advance rate of a tunnel boring machine (TBM). The primary aim of this paper is to investigate tunneling case studies and literature in order to assess TBM productivity from the perspective of ground conditions, tunnel diameter, and project duration. The project data has been tabulated and the results are presented in this paper. The methodology employed for conducting the literature review utilized databases including ProQuest, Engineering Village, ScienceDirect, Google Scholar, and ASCE Library. Additionally, research was conducted on Tunnels and Tunneling International magazine, as well as websites of Tunnel Boring Machine manufacturers. The paper's findings indicate that conducting thorough ground investigations, such as utilizing pilot tunnels, can enhance the efficiency of tunnel construction operations. Various factors affecting productivity in construction projects include the compressive strength of rocks or hard ground, rock abrasivity, tunnel diameter, location of the project (urban or rural), and other variables identified in this study.

Keywords: **Tunnel boring machine, Productivity factors, Tunneling project**

1. INTRODUCTION

The productivity of construction projects has long been a topic of interest for researchers. The complexity of construction projects is notably greater than that of other industries, and the factors affecting project time and cost differ from those in other sectors [1, 2]. For instance, construction projects are characterized by their unique nature, presenting challenges in their management processes. Construction-based projects require increased focus on efficiency, particularly during the initial stages [3, 4].

Tunneling is both a fascinating and challenging discipline within engineering. Tunnel construction consists of three primary processes: excavation, spoil removal, and tunnel support. Various construction tunneling methods include the drill and blast method, TBM, and road header machine. The drill and blast method operates in a cyclical manner, with each cycle comprising four consecutive operations: drilling, blasting, mucking, and installing primary support. The drill and blast method are employed in hard rock tunnels when TBM excavation is not feasible. TBM tunnel construction involves excavating, removing cuttings from the tunnel face, installing a tunnel lining, and extending services and rail tracks. A TBM is utilized for excavating extensive tunnels of varying diameters through a diverse range of soil and rock formations. Excavators and road header machines are employed for distances under 5,000 feet [5]. A road header machine is comprised of a rotating cutting head affixed to the end of a boom attached to a crawler frame.

Tunnel boring machines are categorized based on their diameter sizes. The predominant size category is workers with an entry size exceeding 42 inches. The maximum height for this particular project should not exceed 42 inches. Language: English; for non-worker entry. In utility tunneling projects, pipelines intended for

sewer, water, oil, and gas applications typically fall within the size range of 12 inches. The measurement range extends up to 120 inches. Pipe diameters smaller than 12 inches. Languages are utilized for the distribution of water and gas as well as for service connections [6]. Larger diameter tunnels can extend up to 40 feet in diameter for transportation or storm sewer purposes. The tunneling industry experienced rapid development in the latter half of the 20th century due to the introduction of the first open gripper TBM, designed by James Robbins in 1956 for a sewer tunnel project in Toronto. The TBM with a diameter of 10. 7 feet achieved progress rates of up to 98. 5 feet per day [7]. Implementation of TBMs can partially automate the construction process of tunneling projects. In contemporary construction practices, tunnel boring machines serve as crucial tools in the excavation of tunnels. Tunnels serve as conduits for subterranean transportation of individuals, cargo, and various fluids, such as sewer and gas pipelines. TBMs are utilized for the excavation of circular cross sections with diameters of up to 40 feet and lengths of 1. 33 miles, depending on the tunnel application [8].

2. LITRECURE REVIEW

2.1. Analysis and Prediction of TBM Performance

2.1.1.TBM Selection

Girmscheid and Schexnayder [8] discussed the background of TBMs. The study presented an analysis of various TBM configuration options, along with rationales for selecting a specific configuration. The discussion revolved around the factors influencing the choice of specific tunnel boring machines. The report provided an overview of the significance and operational characteristics of various components of a TBM, such as the cutter head, gripper system, thrust components, and backup system. Furthermore, information was supplied regarding mucking and conveyor systems, with a specific focus on the muck car-rail method. The informational article did not include any analysis or research. Thus, it failed to offer any definitive findings or outcomes.

2.1.2. Performance of New TBM Versus Refurbished TBM

Rostami [9] conducted a comparative analysis of the performance of a new TBM as opposed to a refurbished TBM, as part of the pre-bid assessment for the Jollyville Water Transmission Main WTP4 tunnel project. He conducted an in-depth investigation into the feasibility of utilizing a new Robbins TBM as compared to a refurbished TBM. In his report, Rostami examined the utilization rates of both options and the maximum daily rate of boring. He also addressed the overall project and the tunnel's conclusion. Ground conditions for the Jollyville Transmission Main WTP4 project were ascertained, and this data was utilized for a study on the TBM performance factors. He conducted an analysis and made estimations regarding the rates of production. After conducting his research, he proposed strategies to enhance productivity, including implementing a continuous conveyor system and closely monitoring tunnel ground conditions to prevent project delays. One of the additional recommendations made was to procure and utilize a new TBM as an investment for potential future projects.

2.1.3. Influential Parameters in TBM Performance

The key parameters affecting the performance of tunnel boring machines were discussed by Laughton [10], who delineated the fundamental operational characteristics of these machines and identified the variables influencing their efficiency. He utilized a database to forecast excavation rates by taking into account factors such as performance, machinery, and rock masses. He researched various topics related to tunneling, including the behavior of rock masses and cutterhead penetration. However, the primary emphasis was on TBMs. He aimed to develop a methodology for quantifying the risks associated with tunnel excavation within the framework of the project plan. He explored different methods for removing muck and addressed the challenges related to insufficient data on the penetration rates and productivity of TBMs. Tarkoy [11] outlined the factors that play a role in sustaining the efficiency of TBMs. He examined methods for predicting TBM progress rates and equipment efficiency. He pointed out that the estimated utilization rate is frequently disregarded despite its significant impact as a primary parameter. He elaborated on additional factors affecting TBM performance, which encompass project conditions, management strategies, site constraints, TBM downtime, and the labor force. He noted that several variables rely on human factors, making them challenging to forecast. He determined that excavation rates are likely to deviate by approximately ± 5% from anticipated rates, while utilization rates may deviate by approximately ± 20% from values derived from calculated cycle times, professional judgment, and past experience. Therefore, the utilization factor will have a notable effect on the daily progress rates of a TBM.

2.1.4. Predicting Productivity

In his study, Abd al-Jalil [12] concentrated on optimizing TBM performance and accurately forecasting performance outcomes before initiating tunnel projects. The individual conducted an in-depth analysis of the operational mechanisms of a tunnel boring machine, in addition to examining the production process involved in standard tunnel excavation projects. The objective was to gain a thorough understanding of the variability in time and costs associated with tunnel completion through an examination of four primary factors: 1) the reliability and characteristics of the TBM and back-up system, 2) tunnel variations, 3) geologic conditions, and 4) the overall quality of management. One primary contribution of this study involved compiling data from 12 tunneling projects to establish a database for the development and validation of construction simulation programs. He determined that the performance of TBM is primarily influenced by machine malfunctions and the duration needed for essential maintenance [13]. The objective of this study is to forecast disruptions in tunnel excavation productivity through the utilization of TBMs. The authors noted that significant time was lost as a result of unidentified machine component failures, geological conditions, and inefficient production practices. Two simulation methods were presented, combining the advancement rates of TBMs and facilitating the detection of disturbances. A case study was conducted employing the simulation method to illustrate the operational aspects of the process. The researchers found in their case study comparisons that technical failures have a significant impact on TBM performance. Predicting productivity is a crucial factor for the success of tunneling projects. Hegab [14] conducted a study on the effects of X on Y, finding that Z was significantly impacted. He introduced statistical models to predict the soil penetration rate of micro-tunneling machines based on data collected from 35 micro-tunneling projects. The model parameters selected for consideration encompassed the shear force exerted by the cutter head, jacking length, jacking force diameter, and the duration of tunneling through various soil types. The duration of a micro-tunneling project's penetration time can be accurately predicted using enhanced mathematical models, aiding contractors in estimating the drive's duration. Geological conditions play a significant role in tunneling projects.

2.2. Geological Condition in Tunneling Projects

2.2.1. Geological Uncertainty

The uncertainty of geological conditions is a primary factor in underground construction projects, frequently leading to increased project costs [3, 15]. Numerous researchers have conducted studies to model geological conditions using concepts such as statistical techniques and simulation. Ioannou [16] conducted an extensive research study aimed at reducing uncertainties in underground construction, with a specific focus on tunneling using TBMs. He introduced a comprehensive model for probabilistic tunnel geology prediction, incorporating geological factors such as rock type, joint density, and degree of weathering. Site investigation plays a crucial role in minimizing geological uncertainties, resulting in reduced costs due to decreased contingency amounts in project bids. In a study by Ioannou [16], research findings were presented that elucidate the role of subsurface exploration and enhanced contractual risk sharing in reducing costs associated with underground projects. The major issues delineated include the methodologies employed by tunneling contractors for predicting geological profiles based on available geologic data, the geologic classification techniques used to align expected profiles with viable construction options, and the three-dimensional forecasting of ground classes. He noted the requirement for varying excavation and support methods. Also, he introduced a decision support system designed for evaluating geological exploration programs in underground construction, specifically tunneling with TBMs. The system aims to quantify the economic worth of various subsurface investigation options and establish a consistent framework for stakeholders to make informed technical and financial decisions. He outlined the methodology for utilizing simulation to estimate the expected value and standard deviation of sampled geologic data. The classification of ground types is illustrated in Table1.

2.2.2. Site Investigation and Inspection

Site investigation and inspection are essential for geotechnical design, as they provide the necessary information for interpreting ground conditions [17]. Toll [18] presented a knowledge-based system designed to support geotechnical specialists in processing raw site investigation data to generate interpreted design parameters and a model of ground conditions for computer system interpretation. Oliphant et al. Oliphant and Jowitt [19] detailed the implementation of a knowledge-based system (KBS) with the aim of enhancing substandard site investigation practices. The present study introduces a system known as ASSIST (Advisory System for Site Investigation) consisting of three interconnected sub-systems: preliminary site investigation, data acquisition, and main site investigation. Ioannou [16] discussed the perspective of contractors on the significance of excavating a pilot tunnel within the site investigation program, providing insights on the benefits associated with this practice. The study found that pilot tunnels are beneficial in large-scale projects with restricted surface access and challenging geological conditions. He stated that implementing a pilot tunnel can reduce bid contingencies by up to 20% of the project cost.

Table 1. *Classification of ground based on UCS [17]*

Grade	Description	Field Identification	Range of UCS (ksi)
S1	Very soft clay	Can be easily penetrated for several inches by fist	<0.0036
S2	Soft clay	Can be easily penetrated several inches by thumb	0.0036 -0.0072
S3	Firm clay	With moderate effort, can be penetrated several inches by thumb	0.0072 -0.014
S4	Stiff clay	Easily racked by thumb but penetrated only with great effort	0.014 -0.036
S5	Very stiff clay	Easily Racked by thumbnail	0.036 -0.072
S6	Hard clay	Can be racked with difficulty by thumbnail	> 0.0.72
R0	Extremely weak rock	Can be indented by thumbnail	0.036- 0.14
R1	Very weak rock	Collapses under firm hitting with point of geological hammer, can be peeled by a pocket knife	0.14-0.72
R2	Weak rock	Can be peeled by a pocket knife with difficulty, shallow rack made by firm hitting with point of geological hammer	0.72 – 3.62
R3	Medium strong rock	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with single hit of geological hammer	3.62 – 7.25
R4	Strong rock	It requires more than one hitting of geological hammer for fracturing it	7.25 – 14.5
R5	Very strong rock	Requires many hits of geological hammer for fracturing it	14.5 – 36.26
R6	Extremely strong rock	It can only be chipped with hard geological hammer	>36.36

2.3. Management and Decision Making

2.3.1. Decision Making

Optimal decisions for tunneling plans should be made with the aim of reducing time and cost, taking into consideration factors such as geologic uncertainty, variability, uncertainty in tunneling productivity, and contractor's risk sensitivity [3, 4, 20]. Likhitruangsilp and Ioannou [21] introduced a computerized decision support system that evaluates and integrates key risks associated with tunneling projects. The system can be utilized to establish dynamic optimal tunneling plans and assess risk-adjusted costs within a contractor's risk analysis framework. He and Wu [22] highlight the importance of selecting and designing the appropriate TBM for the specific project. The researchers examined the primary characteristics and variables of rock TBMs, along with the engineering data from finished tunnels. The economic efficiency and overall productivity of the TBM were examined through the estimation and evaluation of the time and cost involved. Afterwards, a computer-based decision support system (DSS) was developed by the researchers. During the design stages, designers of TBMs utilized a DSS for TBM type selection, enabling them to align the appropriate TBM with the corresponding tunnel construction method.

2.3.2. Management

Abdallah [23] conducted a study on the utilization of exploratory tunnels as a tool in project management for estimating costs and determining the necessary time for tunnel construction. Based on data obtained from the Kaponig 1.7-mile exploratory tunnel, a segment of a high-speed double-track railway project in Austria, an assessment of the risks associated with the design specifics for the forthcoming tunnel extension was conducted. A Monte Carlo simulation-based deterministic model was utilized to forecast the probable outcomes of the overall project in terms of cost and duration, along with their respective probabilities.

3. METHODOLOGY

The methodology employed in this paper is depicted in Figure 1. The initial challenge involves assessing the productivity levels of various case studies. Several literature reviews will elucidate various aspects regarding the advancement rate of tunnel boring machines. Multiple case studies were examined in order to gather the necessary data. The evaluation of the collected data will be presented as results and discussion.

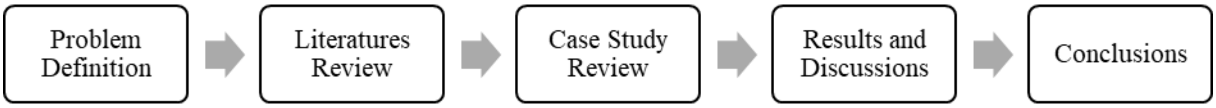

Fig 1. *Research process*

4. DATA OF CASE STUDIES

Data from case studies on various medium and large diameter TBMs are compiled and displayed in Table2. This table provides a concise overview of the case studies reviewed for TBMs. Table 2 displays the productivity, geological composition, tunnel length, uniaxial compressive strengths, diameter, and location of all case studies described in this report. Table 3 displays the data pertaining to small boring units (SBUs), with column descriptors consistent with those found in Table 2.

Table 2. *Summary of case studies for medium and large diameters TBMs*

#	Project	Location	Geology	Length (mi)	Diameter (ft)	UCS range (ksi)	Duration (days)	Avg advance rate (ft/day)
1	La Réunion 1	La Réunion, France	Blocky rocks, basalt, mudstone	5.3	14.1	7-21	985	60
2	La Réunion 2	La Réunion, France	Blocky rocks, basalt, mudstone	1.5	14.1	7-21	180	60
3	Alimineti Madhava Reddy 2	Andhra Pradesh, India	Granite, quartzite, shale	13.5	32.8	23-28	1400	100
4	Mill Creek II	Cleveland, Ohio, USA	Gray chagrin	2.5	23.6	6-12	245	60
5	Yellow River, lot 2	Shanxi Provience, China	Limestone, dolomitic rock	19.9	16.1	6-20	580	120
6	Yellow River, lot 2-2	Shanxi Provience, China	Limestone, dolomitic rock	8.7	16.1	6-20	275	118
7	Yellow River lot 3	Shanxi Provience, China	Limestone, mudstone	13.7	15.7	6-20	790	115
8	Yellow River lot 5	Shanxi Provience, China	Sandstone, limestone, siltstone	8.4	15.7	4-30	365	100
9	Cobb County 1	Georgia, USA	Metamorphic, granite rocks	9.1	18.3	22-33	426	96
10	Cobb County 2	Georgia, USA	Metamorphic, granite	9.1	18.3	22-33	395	96
11	East Side Access 1	NY, USA	Schist, gneiss, granite	1.45	22	14-40	72.5	118
12	East Side Access 2	NY, USA	Schist, gneiss, granite	0.33	22	14-40	55	115
13	East Side Access 3	NY, USA	Schist, gneiss, granite	1.1	22	14-40	20	119
14	Hong Kong Cable	Hong Kond, China	Granit, quartz, volcanic rocks	3.3	15.8	23-29	580	65
15	Kárahnjúkar 1	Fjotsdalur	Basalt, moberg	5.4	23.7	44	365	80
16	Kárahnjúkar 2	Fjotsdalur	Basalt, moberg	5.4	23.7	44	365	85

#	Project	Location	Geology	Length (mi)	Diameter (ft)	UCS range (ksi)	Duration (days)	Avg advance rate (ft/day)
17	Kárahnjúkar 3	Fjotsdalur	Basalt, moberg	5.4	23.7	44	369	75
18	Little Calumet	Illinois, USA	Dolomitic limestone	8	18.2	14-35	365	110
19	Olmos Trans-Andean	Olmos, Peru	Quartz, andesite, tuff	7.7	17.4	8-32	1095	100
20	Pahang Selangor 1	Malaysia	Granitic rock	7.31	17.2	29	863	60
21	Pahang Selangor 2	Malaysia	Granitic rock	7.33	17.2	29	1096	50
22	Pahang Selangor 3	Malaysia	Granitic rock	7.33	17.2	29	1035	55
23	West Qinling Rail 1	Gansu Province, China	Granitic rock	7.33	17.2	4.3-11	1644	65
24	West Qinling Rail 2	Gansu Province, China	Granitic rock	11.3	17.2	4.3-11	1627	70
25	Riyadh (Line5)	Saudi Arabia	Sandstone, phyllite rock	10.33	33.5	7-14	1647	100
26	Riyadh (Line1)	Saudi Arabia	Sandstone, phyllite rock	10.33	33.5	7-14	1647	50
27	Riyadh (Line2)	Saudi Arabia	Limestone	25	32.1	7-14	1647	50
28	Green Line Metro Doha	Doha, Qatar	Limestone	24.2	11.2	7-14	1705	110
29	Red Line Metro Doha	Doha, Qatar	Limestone	15.5	11.2	7-14	852	115
30	Pyrenees Tunnel	Pyrenees mountain, Spain	Limestone, Midra	19	23.1	7-14	365	75
31	Northeastern China	China	Hard Rock	5.5	14	14-36	1095	74
32	Decline Project	Australia	Hard Rock	1.2	26.2	14-36	1095	82

Table 3. *Summary of case studies for SBUs*

#	Project	Location	Geology	Length (ft)	Diameter (ft)	UCS range (ksi)	Duration (days)	Avg advance rate (ft/day)
1	Shayler Run tunnel 1	Ohio, USA	Mixed ground	1,589	72	4-25	92	50
2	Shayler Run tunnel 2	Ohio, USA	Mixed ground	1,888	72	4-25	121	50
3	Shayler Run tunnel 3	Ohio, USA	Mixed ground	1,056	72	4-25	32	50
4	Shayler Run tunnel 4	Ohio, USA	Mixed ground	1,000	72	4-25	30	50
5	Shayler Run tunnel 5	Ohio, USA	Mixed ground	2,014	72	4-25	65	50
6	Shayler Run tunnel 6	Ohio, USA	Hard rock	1,320	72	4-25	31	40
7	Shayler Run tunnel 7	Ohio, USA	Hard rock	646	72	4-25	28	40
8	City of Clinton section 1	Iowa, USA	Hard clay	250	60	10<	49	20
9	City of Clinton section 2	Iowa, USA	Hard clay	270	42	10<	71	20
10	City of Clinton section 3	Iowa, USA	Hard clay	395	72	10<	44	30

#	Project	Location	Geology	Length (ft)	Diameter (ft)	UCS range (ksi)	Duration (days)	Avg advance rate (ft/day)
11	Tahoe Forest Hospital 1	California, USA	Granite	70	30	4-25	9	10
12	Tahoe Forest Hospital 2	California, USA	Granite	70	30	4-25	10	10
13	Tahoe Forest Hospital 3	California, USA	Granite	70	30	4-25	12	10
14	Chester Boulevard Sewer 1	Indiana, USA	Shale and limestone	400	54	10>	10	52
15	Chester Boulevard Sewer 2	Indiana, USA	Shale and limestone	400	54	10>	10	52
16	Chester Boulevard Sewer 3	Indiana, USA	Shale and limestone	180	48	10>	6	60
17	Chester Boulevard Sewer 4	Indiana, USA	Shale and limestone	180	48	10>	6	60
18	Milford Haven Project1	South Wales, U.K.	Siltstone mudstone	1766	48	10-29	15	60
19	Milford Haven Project2	South Wales, U.K.	Siltstone mudstone	1766	48	10-29	16	60
20	Milford Haven Project3	South Wales, U.K.	siltstone mudstone	1766	48	10-29	17	60
21	Kota City Project	Rajasthan, India	Quartzite rock	164	60	29-36	3	50
22	Kota City Project	Rajasthan, India	Quartzite rock	164	60	29-36	3	50
23	Glenwood Cable Tunnel	Southern Connecticut, USA	Quartz	220	60	5-20	6	40
24	Glenwood Cable Tunnel	Southern Connecticut, USA	Quartz	220	60	5-20	7	40
25	Locust Project 1	Oregon, USA	Clay, basalt	230	42	7-12	3	80
26	Locust Project 2	Oregon, USA	Clay, basalt	600	42	7-12	8	80
27	Locust Project 3	Oregon, USA	Clay, basalt	320	42	7-12	4	80
28	North Carolina	North Carolina, USA	Gabbro	118	66	14-36	8	14.5
29	Big Sky	Montana, USA	Mixed ground	216	30	4-25	5	40

5. DISCUSSION OF CASE STUDIES

The results of the case studies are outlined as follows:

- The productivity of TBM is reduced in a minority of case studies due to an increase in the tunnel diameter.
- Geotechnical conditions have an impact on TBM productivity. The case studies illustrate that the average productivity in limestone is 80 ft per day, in sandstone it is 90 ft per day, and in granite it is 55 ft per day.
- The average productivity is 80 ft per day in urban areas and 90 ft per day in rural areas.
- The Locust Project in Oregon, USA, achieved the highest average advance rate of 80 ft per day among all small diameter projects. The project site featured clay and basalt soil with an unconfined compressive strength (UCS) ranging from 7 to 12 ksi and a depth of 42 inches.
- The Thao Forest Hospital project in California, USA exhibited the lowest average advance rate of 10 feet per day compared to other small diameter projects. The project's ground consisted of granite with a UCS of

25 ksi and a thickness of 30 inches.
- The Yellow River Project in Shanxi, China demonstrated the highest average daily advancement rate of 120 feet among projects categorized with diameters exceeding 10 feet but less than 20 feet. The project site was composed of limestone, dolomite, and mudstone with a UCS ranging from 6 to 20 ksi and a diameter of 16 ft.
- The Pahang Selangor project in Malaysia attained the slowest average advance rate of 50 ft per day among projects with diameters exceeding 10 ft but less than 20 ft. The ground primarily consisted of tough, abrasive granite with UCS of 30 ksi and a diameter of 17 feet.
- The East Side Access Project in New York, USA, attained the highest average advance rate of 120 feet per day among projects with diameters exceeding 20 feet but less than 40 feet. The project encountered varying soil conditions with UCS ranging from 14 to 40 ksi and a 22 ft diameter.
- Up to this point, the first and second lines of the Riyadh Metro System project in Saudi Arabia have achieved the lowest average advance rate of 50 ft per day among projects with diameters between 20 ft and 40 ft. The diameters of line 1 and line 2 measure 33.5 and 32.1 feet, respectively. The ground composition encompasses sandstone, phyllite, and limestone, with a UCS range of 7 to 14 ksi.

6. CONCLUSIONS

The following list presents the conclusions of this research:
- Geotechnical conditions significantly influence TBM productivity.
- Productivity in urban areas (80 ft per day) is lower than in rural areas (90 ft per day) due to workspace limitations.
- Small diameter projects achieved an average advance rate of 80 ft per day.
- Small diameter projects also achieved the lowest average advance rate of 10 ft per day.
- Projects with diameters over 10 ft and less than 20 ft had the highest average advance rate of 120 ft per day.
- Projects with diameters over 10 ft and less than 20 ft also had the lowest average advance rate of 50 ft per day.
- Projects with diameters over 20 ft and less than 40 ft achieved the highest average advance rate of 120 ft per day.

Due to constraints in time and resources, this paper did not undertake an exhaustive examination of TBM productivity. Thus, the recommendations for future research can be summarized as follows:
- Data collection from actual projects taking all factors into consideration.
- Statistical analysis and modeling of TBM productivity.
- Conceptual cost estimating of TBM usage for various diameters, site conditions, and project circumstances.

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