Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds)

Overview of soft ground TBM performance

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ABSTRACT: The Norwegian University of Science of Technology (NTNU) has a long tradition in preparing empirical prediction models for tunnelling and construction work in rock and soil. Hyundai Engineering and Construction has cooperated with NTNU in gathering TBM production data from recent soft ground tunnelling projects. This research paper aims to present how TBM performance is ranging for various TBM diameters, as well as qualitatively describe how various ground conditions influence the tunnelling performance. The data originates from 9 tunnelling projects, with tunnel diameter from approximately 2 m to more than 12 m. The soil conditions within the collected data range are varying from cohesive soils (clay and silt), to frictions soils mainly consisting of sand and gravel.

1 INTRODUCTION

One of the many aspects a tunnel owner and designer will estimate in early phase tunnelling, is the possible advance rate of the tunnelling performance. Estimation of TBM performance involves the study and the understanding of (1) how a TBM can penetrates the soil (and rock), (2) which ground parameters are involved in the excavation process, and (3) how the different types of machines are operated. Finally, the importance of a reliable estimation of advance rate as a function of geology and TBM parameters grows with years. Research related to mechanized TBM tunnelling has mainly focused on hard rock performance e.g., by Macias (2016) and Yagiz (2014).

The NTNU (Norwegian University of Science and Technology) prediction model for hard rock TBM tunnelling that has been upgraded several times since the first version was published in 1976, see Table 1. The model is commonly used for estimating the advance rate, cost and tool life for hard rock TBM tunnelling.

For soft ground TBM tunnelling the research has been on lab-scale TBM performance and experiences from one project e.g. An et al. (2011), Lee et al. (2019) and Kim (2018). Another topic related to soft ground TBM tunnelling is tool life predictions by e.g., Jakobsen and Lohne (2013), Hunt and Del Nero (2019). The estimation mechanism of advance rate in soft ground is quite different from the one in hard rock. While hard rock excavation is normally inducing brittle failures into the rock mass at the tunnel face, soft ground excavation with TBM is based on scraping and ripping looser fragments in a confined environment with face stabilization.

In order to study soft ground TBM excavation performance, Hyundai Engineering and Construction and NTNU carried out a joint research. This paper summarizes the research efforts and gives examples of results that have been achieved during the research project. The general information of the research project is listed in Table 2. The project was carried out in 2016-2019 and included collecting TBM performance data such as e.g., mm/minute performance, TBM utilization together with ground conditions.

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Table 1. Editions of the NTNU hard rock TBM prognosis model (after Macias 2016).

Edition	Year	Remarks
1st	1976	Relations between TBM diameter, Drilling Rate Index (DRI) and performance. Tool life and cost according to the Bit Wear Index (BWI).
2nd	1979 (published in 1981)	As 1976 with higher influence of rock mass fracturing and orientation.
3rd	1983	As 1979 and introduction of Cutter Life Index for estimating cutter tool wear. Improved utilization model.
4th	1988	As 1983, more empirical data and increased geology database and TBM sizes.
5th	1994	As 1988 more empirical data and increased geology database and TBM sizes.
6th	2000	As 1994 more empirical data and increased geology database and TBM sizes.
7th	2016	As 2000, more empirical data and increased geology database and TBM sizes. Influence on TBM operation and rock mass fracturing on tool life estimation.

Table 2. Activities executed by Hyundai E&C and NTNU in the joint research project.

Institution	Activities
Hyundai	• To construct the TBM database of the TBM projects in Korea and South East Asia • To development of the Soil Abrasion Penetration (SAPT) test+ • To investigate the effects of agents such as foam on the performance of TBM excavation in soft ground
NTNU	• To construct the TBM database of the TBM projects around world • To analyse the correlation and sensitivity of general information and soft ground parameters with TBM design parameters and TBM performance parameters • To establish the concept of new test method to enable the prediction of full set or parts of the TBM design/performance parameters

An important part of the joint research was to gather TBM performance data such as TBM performance (mm/rev, mm/minute, TBM utilization etc.) together with ground conditions. The data that provides examples in this paper originates from 9 sites with general information in Table 3.

Table 3. Project with corresponding TBM type, diameter and length.

Project number	Face support	Approximate diameter [m]	Approximate tunnel length included in the study [m]	Region
1	Slurry	12.5	1100	Europe
2	EPB	6.5	900	Asia
3	Slurry	3	400	Europe
4	Slurry	2.5	300	Europe
5	Slurry	2.5	900	Europe
6	Slurry	3.5	700	Middle East
7	Slurry/EPB	5.0	5400	America
8	Slurry	13	4500	Middle East
9	EPB	7,5	530	Asia

2 RESEARCH METHODS

The joint study comprised:

– Literature review
– Field studies to collect data and soil samples
– Laboratory testing of obtained soil samples

Various published papers and experiences from recent tunnelling projects have been used to track down additional information about specific topics and projects. In some projects where the TBM field data have been gathered, information about soil conditions have been gathered from literature review.

The research plan of the joint project is presented in Table 4. During the research, the toughest effort has been to obtain field data and gathering of TBM production data. The data is often difficult to gather, as the TBM production reveals contractor's performance and consumption. Such information is often treated as sensitive and confidential for parties without any formal involvement in tunnelling contracts. In order to obtain data, it has been necessary to establish confidentiality agreements with contractors and data owners, and to avoid publishing and sharing site-specific data.

Table 4. Initial summary of research plan to establish a database with findings and plan for analyses.

	Category	Information
Collected data	1. General information of the project	Project name, Location, Tunnel length, Tunnel diameter
	2. Geological conditions	Soil type, Soil size (i.e., Cu index, D50), Density, SAT, Quartz content, Cohesion, Friction angle
	3. TBM Specification	Excavation method (EPB, Slurry), TBM model, Diameter, Manufacturer, Number of cutter tools, Pictures of head face
	4. Operation data of TBM	Location of TBM, performance, RPM, thrust force, torque, utilization and chamber pressure at each recorded time,
Analyzed results	Penetration rate (mm/min, mm/rev), Advance rate (daily, monthly), Tool replacement rates, Tool life, Machine utilization. Analyses of relations between the mentioned parameters are also included in the study.	

The projects included in the study have been selected on the basis of the following:

– Variety of ground conditions
    ○ Soil lithology in order to include data from clay, silt, sand and gravel
    ○ Overburden and thus shear strength
– A variation of excavation method (EPB and slurry face support)
– Variation of TBM diameter
– Variation of contractors and project owners.

3 RESULTS

In the following some of the results of the collected data is presented. Figure 1 shows boxplot of the recorded net penetration rate in mm/min for the 9 projects. Project 3 to Project 6 are small diameter TBMs, with high recorded net penetration rate. However, the advance rate in m/week is relatively low due to low utilization or boring time. Figure 2 to Figure 5 shows more detailed data for Project 1 on penetration rate, torque and utilization, and how this varies dependent on the ground conditions (sand, gravel and clay).

Figure 2 shows how the excavation rate in m/h varied along the tunnel drive in Project 1. Project 1 was a 12.5 m diameter mix-shield TBM in various ground conditions. The changing excavation rate the first 150 m is not related to the ground conditions but running in the TBM and its crew. In addition, the data is influenced by pulling back and pushing forward the TBM in the launch area. The colour legend (light green, yellow and green) presents the percentage of sand, gravel and clay size grains along the drive.

Figure 3 shows the penetration rate in mm/rev for Project 1.

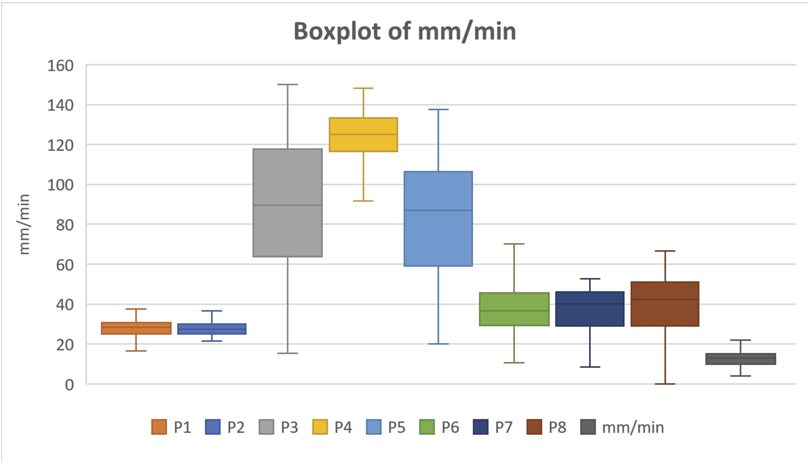

Figure 1. Boxplot of recorded net penetration in mm/min for Project 1 to Project 9.

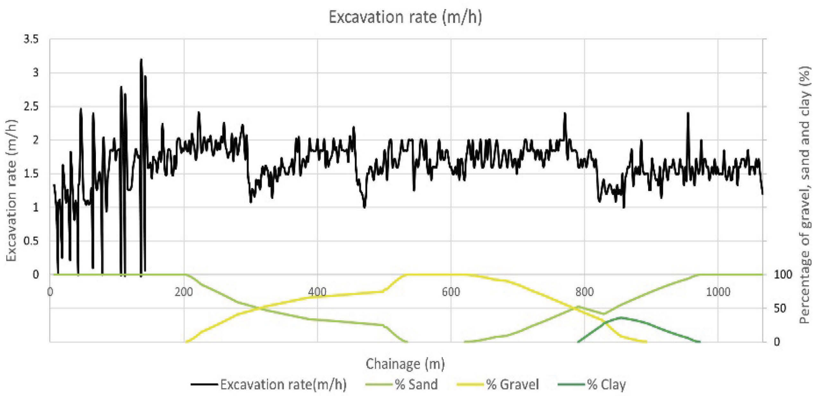

Figure 2. Excavation rate for Project 1.

Figure 4 shows the recorded torque for Project 1. The torque has been relatively constant during the drive, with a high peak in an area with well-graded soils containing clay, sand and gravel fractions.

Figure 5 shows the utilization for Project 1, which ranges from 15-20 % boring time. The utilization is not influenced by the variety of ground conditions.

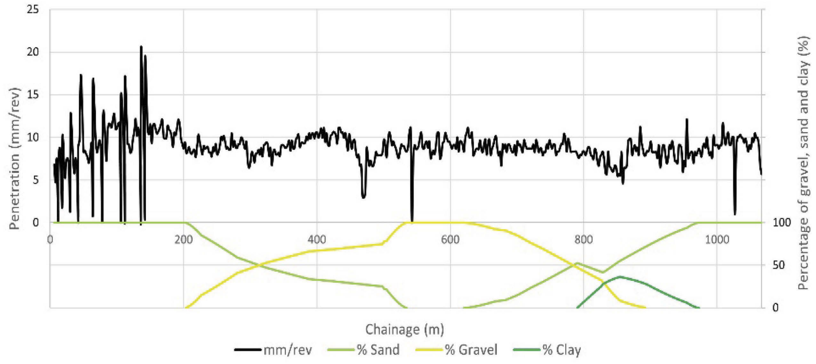

Figure 3. Penetration rate (mm/rev) for Project 1.

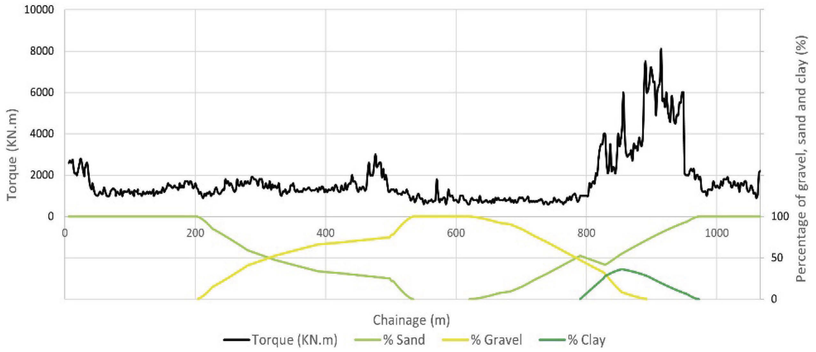

Figure 4. Torque (kNm) for Project 1.

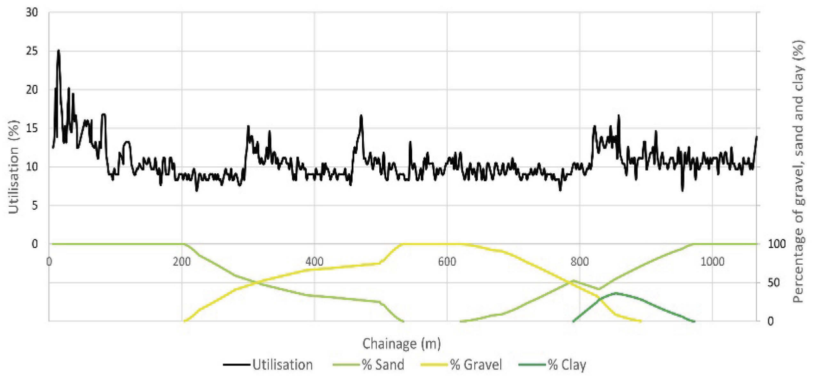

Figure 5. Utilization (time usage for boring divided on available working time) for Project 1.

Figure 6 shows the relation between the TBM excavation diameter and the average torque per project. Project 8 is the same project as described in the previous figures with zones consisting of a variety of clay, sand and gravel. The TBM type was a slurry shield TBM.

Project 3, 4 and 6 originates from small diameter slurry TBMs in single graded sands. (D50 values from 0.275 to 0.33.). Project 2 is a 6 m diameter TBM also excavated in sandy and gravely material with slurry. Project 9, which deviates most from the linear trendline in Figure 6 is from a EPB project in cohesive ground. The relation between torque demand and

TBM diameter seems to be much stronger that between the torque demand and ground conditions, with the current data set and average values of torque.

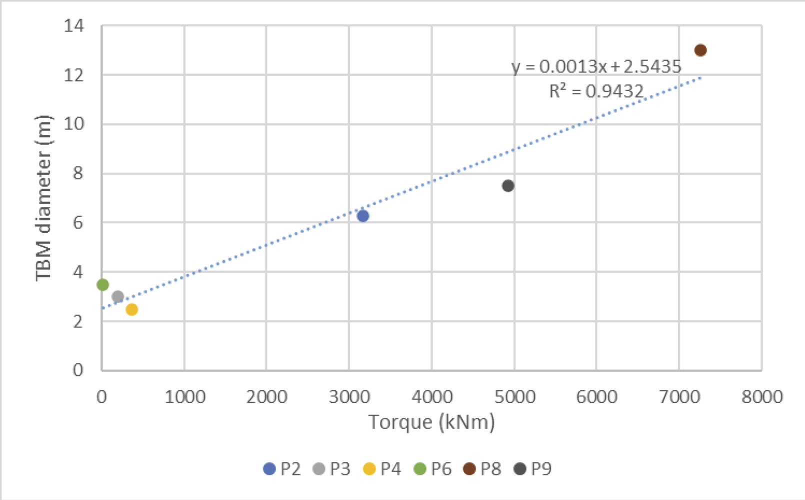

Figure 6. Relation between TBM excavation diameter and average recorded torque per project.

Table 5 shows average values of geotechnical data and recorded TBM operational data. The average values have been used to make several bivariate regressions between TBM operation (e.g., mm/min) and other factors.

Table 5. Average recorded TBM values per project for various soil lithologies.

Project	Diameter	opening r	Soil type	D50	Cu	Advance r	Thrust	Torque	RPM	Unit weigl	Friction ar	Cohesion	Average s
	m					mm/min	kN	kNm					kPa
P1	12.5	0.324	Gravel	2.2	38.6	28.4	40020	852.6	2.1		38	0	149.2955
	12.5	0.324	Sand	0.6	2.4	27.3	33590	1395.2	1.8		35	0	80.37122
	12.5	0.324	25%clay75%sand	0.4	4.2	24.1	39700	6333.3	2.2		35	74	72
P3	3	0.324	Medium sand	0.275	3.825	87.9	747650	194.3		18.5	36.25	0	94
P4	2.5	0.324	Medium sand	0.33	2.3	114	279180	363	1.9	18.5	32	0	57.28201
P5	2.5	0.324	Medium sand	0.2363	2.9	90.8	48219			18.5	35.2	0	110.25
	2.5	0.324	Gravel	3	55	116.7	18893			20	35	0	60
	2.5	0.324	Silt	0.0365	55	68.4	42768			21.5	27.5	11	109.3487
	2.5	0.324	Silt	0.0152	12	96.3	29829			19.5	26.3	6	99.11579
	2.5	0.324	Fine sand	0.1259	4.3	88.6	29665			19	32	0	88.45625
	2.5	0.324	Fine sand	0.1364	29	70.4	46316			20	32	22	113
P6	3.5	0.4	Sand	0.1	3.8	39.1	5796	17.21	4.2		28	15	
P8	13	0.35				40	78607	7262.6	1.57		32	22	
P7	5	0.27	Sand/silt	0.27	10	38					36	22	
	5	0.27	Gravel	22.5	38	29					38	0	
	5	0.27	Gravel	13.67	144	39.8					38	0	
P9	7.5	0.543	Gravel	5.75	132	17	239818	4932	1.6	20	35	50	92.67164

It has been found a fair correlation between mm/min and TBM excavation diameter, as presented in Figure 7. When it comes to other relations the R^2 values indicates poor correlations. An example showing the relation between the soil cohesion and net penetration for the TBM is presented in Figure 8. For some of the data points the cohesion is 0, as the soil contains pure friction soils (sand and gravel). This influence the R^2 and the validity of the regression.

4 DISCUSSION AND FURTHER WORK

The initial hard rock TBM performance database prepared by NTNU (former NTH) in the 1970's based its estimation of mm/rev and mm/min on the Drilling Rate Index (DRI) and TBM

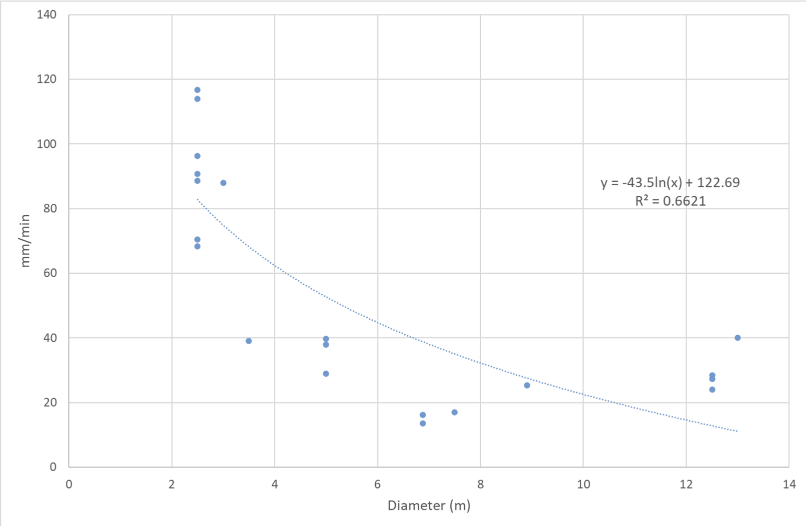

Figure 7. Regression between TBM excavation diameter and net penetration rate in mm/min according to the data in Table 5.

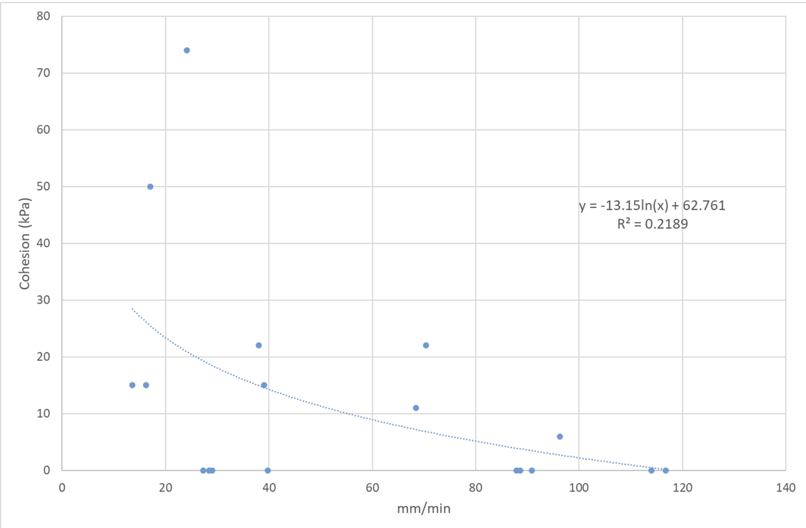

Figure 8. Regression between soil cohesion (kPa) and net penetration rate in mm/min according to the data in Table 5.

diameter. Slowly as more TBM and geological data derived from tunnelling projects, the model now includes tens of input parameters to estimate advance rate, utilization, tool life (Macias 2016).

Based on the collected and current data for soft ground TBMs, there are plans to generalize and utilize multivariate regression in order to find predictors of e.g., TBM torque, penetration rate based on geotechnical properties and TBM size. With data from 9 projects, there is not sufficient amount of data to enable a valid prediction. Especially when the data quality ranks from recorded data per second, to per hour and per shift. Another challenge in enabling prediction is the density of ground investigations that are used as geotechnical parameters. It is quite common to encounter a variety of ground conditions between geotechnical core drillings. How the geotechnical properties are interpreted in between the available core drillings and subsequent laboratory tests will highly influence the predictions.

In the further work the following activities and research are planned:

- Collect high quality TBM data from additional TBM projects in soft ground.
  - By high quality it should be data recording every 10 seconds, and with either homogenous ground conditions or close geotechnical drillings
- Enable an anonymous database with generalized data, for artificial intelligence/Machine learning/data scientists. The authors believe that several interesting findings can be aggregated by utilizing AI/ML techniques, given that the input data is good enough.

5 CONCLUSIVE REMAKRS

Hyundai Engineering and Construction has executed a joint research project on soft ground TBM performance. Some of the recorded TBM data has been presented in this research paper, to show the span in TBM performance, utilization, TBM diameter, ground conditions, as well as the data quality. The current collected data and utilized methods is not sufficient to establish a reliable prognosis model of soft ground TBM performance for various TBM diameters and varying ground conditions. In contrary, the authors believe that the study can be a start for further research, and that the gathered data show the "state-of-the art" in soft ground TBM performance. Further, some relations between TBM diameter, torque and performance can be evaluated with the graphs presented in this paper.

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