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A Preliminary Study: Influence of Sub-Surface Ground Condition on the Tunnel Boring Machine Performance

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Abstract. Tunnelling through various ground condition affects the performance of Tunnel Boring Machine (TBM). Previous researches have conducted studies to explain on this relationship. However, a more localised influence of Malaysian Kenny Hill Formation subsurface condition towards TBM drive are yet to be carried out. This study will assess this relationship at areas nearby Museum Station during the Klang Valley Mass Rapid Transit (KVMRT) Line 1 with a length span of 540m. After the data collection from TBM and borehole report, data analysis was carried out namely using cutter head, thrust cylinder and subsurface profiling. These data were plotted based on the chainage and tunnel ring number. It is observed that subsurface profile at Ring 9 and Ring 11 required a higher thrust force due to its cohesive soil condition and inclusion of sandstone rock. However, Ring 10 is vice versa as there were more non-recovered soil samples at the specified area. The reduction of thrust force eventually increases the speed of TBM penetration. Thus, a clear relationship showing that subsurface condition highly influences the TBM drive.

1. Introduction

Tunnelling activities have been major alternatives to reduce the traffic congestion and limited land space in major cities in Malaysia which forbids future development. With the increasing population and demand, Malaysia has opted to this alternative according to Sustainable Development Goals that specify life on land and sustainable cities [1].

However, during the tunnelling process, the problem arises when the subsurface conditions are not so favourable [2]. This will affect the Tunnel Boring Machine's (TBM) performance. Therefore, tunnel linings are installed once the excavation process is completed. Nevertheless, geological conditions play an important role in influencing the excavation process. Various researchers conducted studies on the influence of ground conditions on the TBM performance. Yet, a localised study in Malaysian ground conditions is relatively limited in terms of preliminary studies. Hence, this study will show the results achieved via the objectives set alongside the relevant framework.

2. Objective

The main aim of this study is to assess the performance of the Tunnel Boring Machine (TBM) drive of the tunnelling project site. In order to solve this aim, these objectives must be achieved as follows:

- To identify and classify important parameters from the TBM report
- To analyse the nearest Soil Investigation report
- To assess the factors influencing the TBM drive

3. Methodology

The methodology used for this study is shown in Figure 1. A simple operational framework was conducted to solve the objectives by stages. Based on Figure 1, there are 4 stages to be carried out before completing this study. Therefore, this aids in completing the main aim of this paper.

Figure 1. Operational framework for the purpose of this research.

4. Background of Study Area

This study is solely based on the secondary data received from the Mass Rapid Transit Line 1 (MRT Line 1) Technical team. This project is also known as the Semantan North Portal – Pasar Seni Klang Valley Mass Rapid Transit Line 1, which bounds in the North (NB) and South (SB) directions. The total length of the bored tunnel using the Tunnel Boring Machine (TBM Serial Number: crec050) is approximately 520m starting from Gerakan Belia 4B Malaysia till Orang Asli Craft Museum (refer to Figure 2). The tunnel diameter adapted in this project is uniform along the boring length is 6.35m. While the method of tunnel boring used is shield tunnel type associated with TBM.

Figure 2. Location of tunnel bored studies.

The TBM used involves using automated tunnel ring installation once the subsurface profile is bored out using the screw conveyor. The tunnel rings are numbered starting from R916 to R1121 for NB while R902 to R1109 for SB. These tunnel rings are located in between NB 2+384 to NB 2+830 and SB 2+360 to SB 2+800. Furthermore, detailed TBM numerical data was provided for the range of the tunnel rings stated previously. In addition to the TBM numerical data presented, the project location is underlain by Kenny Hill Formation. The subsurface profile here comprises of silt with Standard Penetration Test (SPT) N-value of 50 and weathered sandstone. The relationship between TBM data and these geological profiles will be discussed thoroughly in the next chapter.

5. Results & Discussion

Data entry and collection were carried based on the utmost important parameters, as shown in Table 1.

Table 1. List of data and parameters captured from the given TBM report of each rings.

Item	Data / Parameters		In Terms Of
1	Chainage		NB or SB
2	Ring Number		R
3	Cutter Head	Rotation	r/min
		Torque	kN.m
		Pressure	bar
4	Thrust Cylinder	Total force	kN
		Speed	mm/min

By referring to Table 1, the selection of data shows the overall operation of TBM during the subsurface profile boring process till the installation of the tunnel ring [3]. This dataset collected is then plotted graphically to observe TBM's trend with Item 1 and 2.

Besides that, Item 3 and Item 4, especially cutter head torque and total force of thrust cylinder are the most critical parameter that needs to be focused in this study. According to [4], these two parameters can evaluate the interaction of TBM during subsurface excavation works and the machine's overall performance. Theoretically, a weaker subsurface profile will result in higher torque development when provided a constant thrust force [5]. A simple graphical correlation was plotted for each ring type at NB and SB, as shown in Figure 3 and Figure 4, respectively.

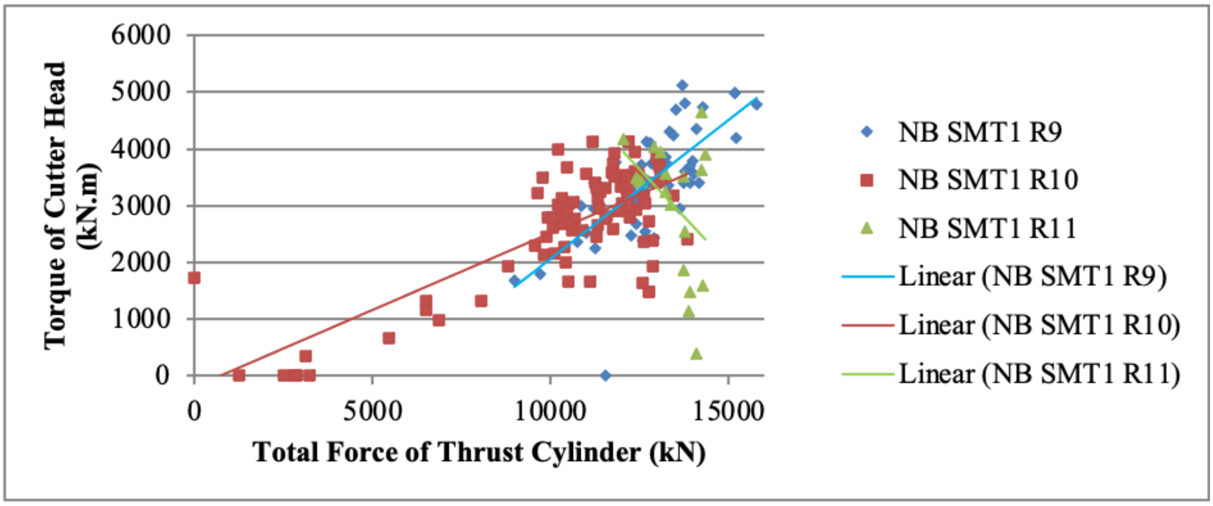

Figure 3. Relationship between the total force of thrust cylinder and torque of cutter head for NB.

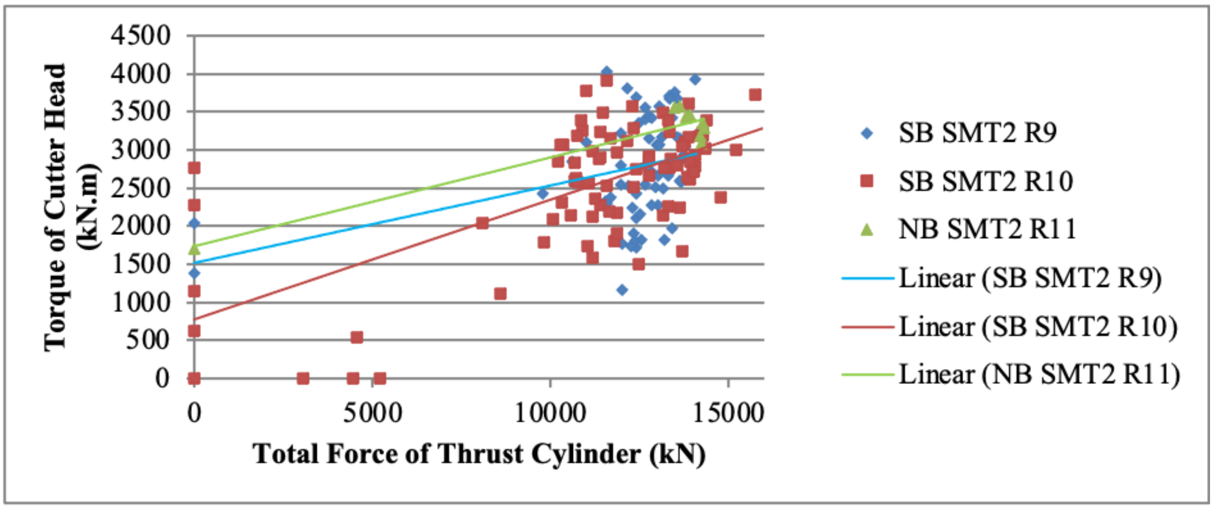

Figure 4. Relationship between the total force of thrust cylinder and torque of cutter head for SB.

From the graphs shown in Figure 3 and Figure 4, an increasing trend between the parameters was generally observed. A higher torque supplied by the more significant thrust force shows that the boring machine encountered a hard subsurface condition during the excavation works. This type of subsurface condition possesses a lower weakness plane which requires a greater force to be exerted on it to ease the penetration of TBM [6]. A similar trend line was observed during the correlation between thrust ranging from 4000 kN to 28000 kN and torque ranging from 0 to 10000 kNm of TBM where the coefficient of determination, R^2, was ranging from 0.5140 to 0.8682 [7].

However, a decreasing linear trend line was observed for NB SMT1 R11 as shown in the green coloured line in Figure 3. Numerically, Ring 11 (R11) at SB SMT2 shows a similar trend line if the first point of anomaly (0, 1698.15) is removed. This could be due to the weaker subsurface condition or infill cavities that required a lower thrust and torque for cutter head penetration. The lack of a complete dataset for R11; such as the nearest borehole data and TBM parametric report may also cause the inconsistent trend line. A clearer picture on the dataset obtained can be observed when comparing these parameters based on the reference number of ring, as shown below in Figure 5 and Figure 6.

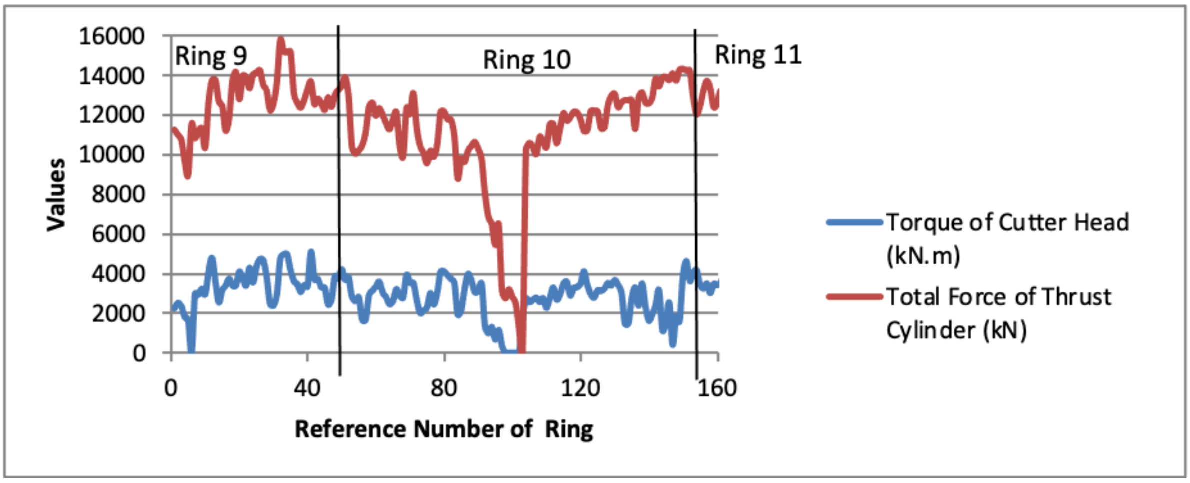

Figure 5. Excavation torque of cutter head and total force of thrust cylinder with reference to the ring number at NB SMT1.

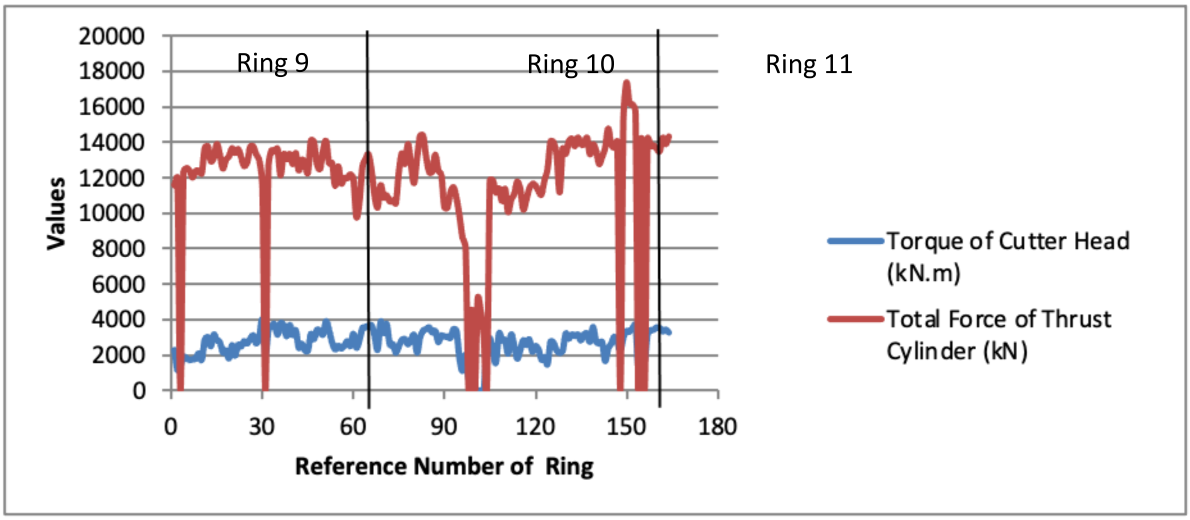

Figure 6. Excavation torque of cutter head and total force of thrust cylinder with reference to the ring number at SB SMT2.

Based on Figure 5 and Figure 6, Ring 9 and Ring 11 shows high cutter head torque and thrust cylinder force compared to Ring 10, where a significant drop in these values was observed. This can be related and explained based on its geological condition at the specified ring numbers. Since R11 has insufficient borehole data, the larger values observed at R9 are based on the Borehole 11 Report 40 (Table 2). While, lower values of R10 are due to the Borehole 12 Report 40 and Borehole 14 Report 40 as shown in Table 3 and Table 4 below, respectively.

Table 2. Borehole report for Ring 9 at NB SMT1 and SB SMT2.

Data	NB SMT1 and SB SMT2 Ring 9 (BH11 Report 40)
Ground level	32.414 mRL
SPT-N 50 Silt	23.414 mRL
Hit rock level	10.214 mRL
End of Borehole	3.214 mRL

Table 3: Borehole report for Ring 10 NB SMT1.

Data	NB SMT1 Ring 10 (BH12 Report 40)
Ground level	32.817 mRL
SPT-N 50 Silt	22.317 mRL
No recovery	16.317 mRL
No recovery + SPT-N 50 Silt	13.317 mRL
End of Borehole	4.067 mRL

Table 4: Borehole report for Ring 10 at SB SMT2.

Data	SB SMT2 Ring 10 (BH14 Report 40)
Ground level	37.693 mRL
SPT-N 50 Silt	31.693 mRL
No recovery	24.193 mRL
1st Hit rock level	22.693 mRL
No recovery + SPT-N 50 Silt	18.193 mRL
2nd Hit rock level	12.193 mRL
End of Borehole	2.893 mRL

Table 2 to Table 4, the yellow highlighted box denotes the location of tunnel bored using the TBM. The tunnel centerline is along the 15 mRL mark, where the tunnel diameter of 6.35 m shows the tunnel crown and toe is at 18.175 mRL and 11.825 mRL, respectively, as shown in Figure 7. While the overlay of the tunnel alignment on the subsurface profile are shown on the bar chart in Figure 8.

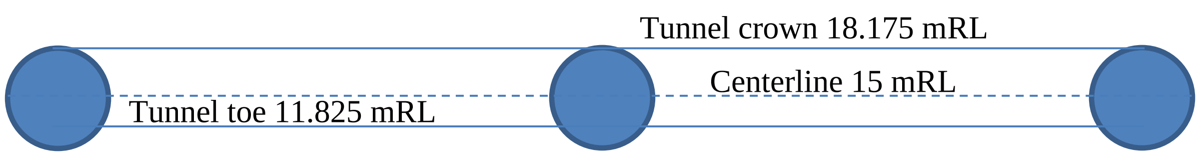

Figure 7. Tunnel dimension and levels for the studied project site.

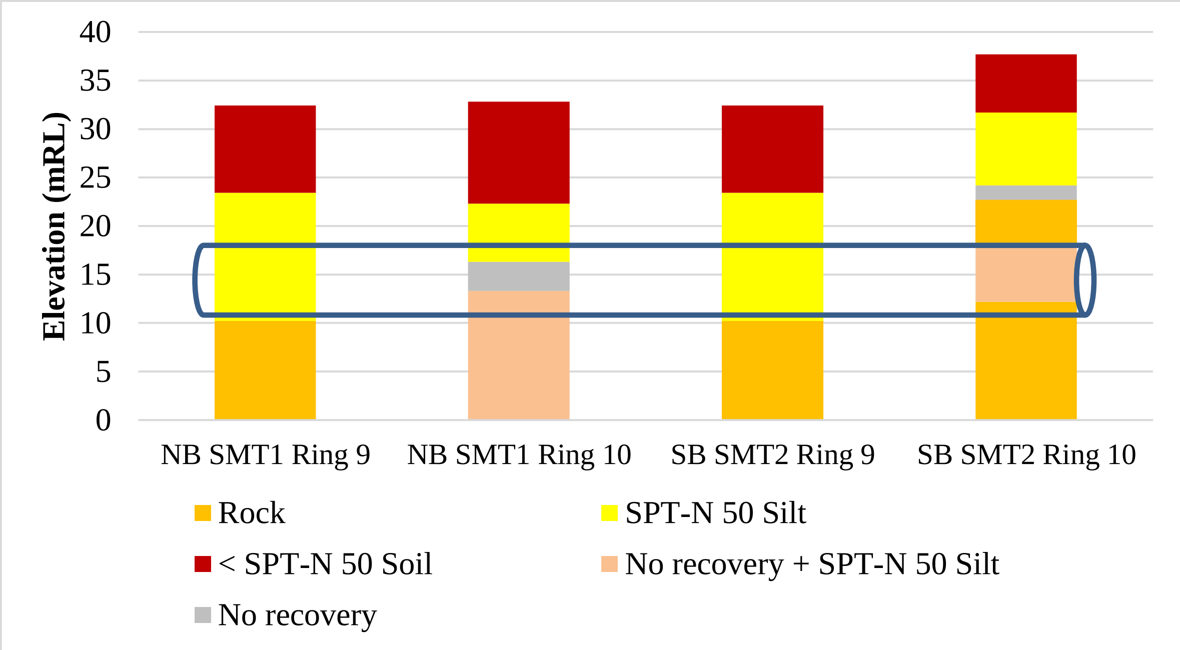

Figure 8. Overlay of tunnel alignment onto the subsurface profile obtained from the borehole data.

Based on the borehole reports, there are some differences in terms of geological conditions from Gerakan Belia 4B Malaysia till Orang Asli Craft Museum albeit the short span of length. According to Wallis (2015) [8], the main geological formation that underlain these study areas are the Kenny Hill Formation (Figure 9). This formation comprises interbedded clastic sedimentary rocks such as sandstone, siltstone, and shale.

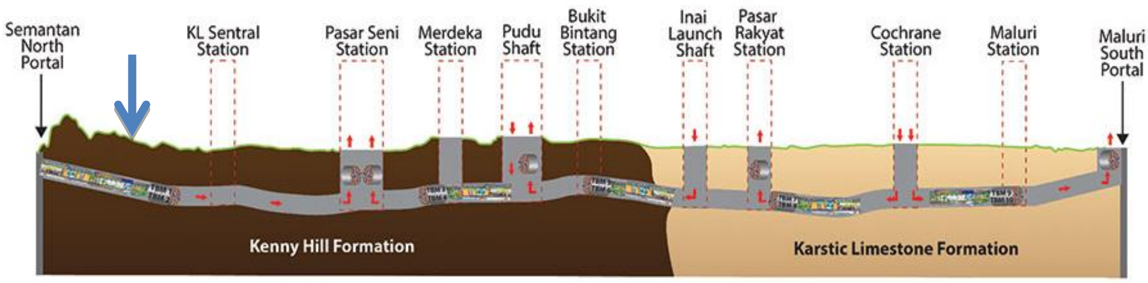

Figure 9. Tunnel drive and an indication of Museum Station via the blue arrow [8].

The differences in the subsurface profile mentioned previously are observed in Figure 8. The NB TBM goes through various profiles starting with silt with Standard Penetration Test (SPT-N) of 50 blows and a mixture of profiles with no sample recoveries. A similar TBM drive was observed at SB TBM, but it ends at profiles consisting of sandstone rock and no sample recoveries of soil.

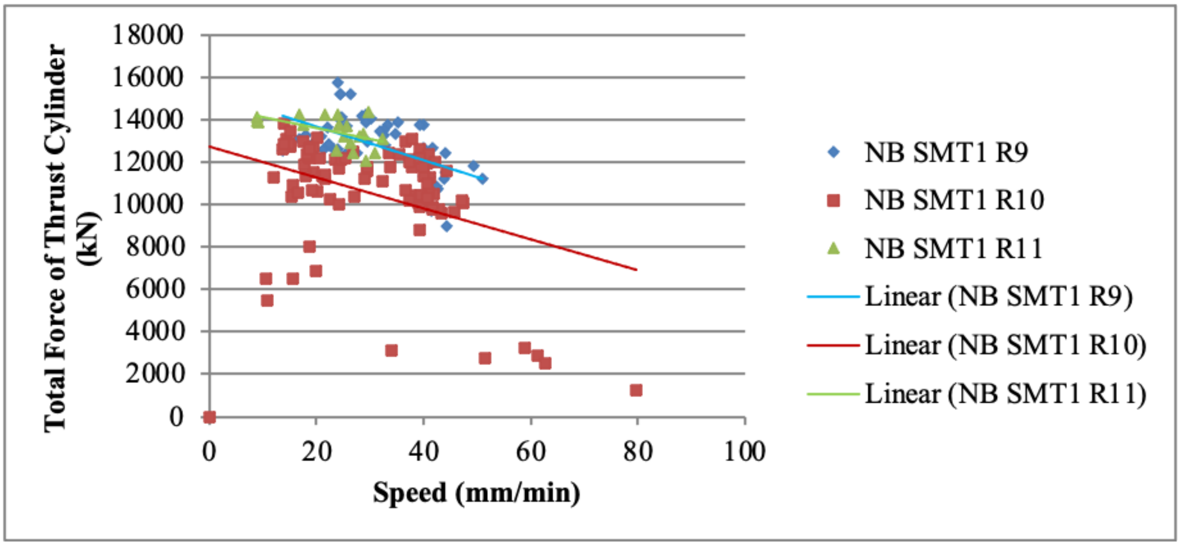

Figure 10. The relationship between total force and speed of thrust cylinder during TBM drive.

The inclusion of subsurface profiles consisting of the non-recovery samples shows that the soil type is non-cohesive and easily lost during the wash boring process. A similar process is done during the TBM movement. This eventually reduces the force needed by the TBM to penetrate through these profile types. Thus, the drop of TBM drive at Ring 10 for both NB and SB are proven in this matter. Theoretically, the decline of TBM thrust force will increase the penetration speed, which can be shown in Figure 10. This is due to the lesser work done required to penetrate weaker subsurface profiles. The validation of this statement are shown via the decreasing trend of about 18% was observed between the thrust force ranging from 26000 kN to 34000 kN and advance rate ranging from 16 mm/min to 66 mm/min during the Beheshthabad water conveyance tunnel excavation [9].

6. Conclusion

This study was based on secondary data along the alignment of completed tunneling sites surrounding the Museum Station of the KVMRT Line 1. This study has answered all the 3 objectives outlined in this paper. Firstly, the TBM data that were classified important in this study were cutter head and thrust cylinder parameter that focuses on the TBM performances. Secondly, the subsurface profile was plotted and analyzed using the SI borehole data. In general, the SPT-N 50 Silt, no recoveries (N/R) samples, and highly weathered sandstone were observed in the plotted profile. Thirdly, this TBM performance was successfully related to the influence of the geological profile. A higher torque and thrust force was needed whenever TBM penetrates through harder subsurface conditions like sandstone and cohesive SPT-N 50 silt. This situation was observed at Ring 9 and Ring 11 of both NB and SB TBM. Besides that, a sudden drop was observed in Ring 10 in relation to these values. This is due to the major non-recovered weak samples in the subsurface profile during TBM excavation. Furthermore, this drop in TBM drive causes a decline in total force but an increase of penetration speed. In a nutshell, the overall results obtained from the relationship between SI and TBM data are complementing and in line with each another. Thus, a subsurface condition highly influences the TBM performance in a localized area based on this study.

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