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Significant Parameters Affecting Mix-Shield TBM Performance in Clay Soils

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الملخص:

فى مشروعات الانفاق الحديثة، غالباً ما يتم استخدام ماكينات حفر الانفاق بدلاً من اساليب حفر الانفاق التقليدية. قطاع ماكينات الحفر بشكل عام يكون دائرى بقطر يتراوح مابين 1 متر إلى 19 متر اعتماداً على اسباب استخدام النفق الذى من الممكن ان يكون نفق صغير للمياه الجوفية او الصرف الصحى أو نفق كبير للطرق والسكك الحديدية ومترو الانفاق.

معظم ماكينات الحفر لديها العديد من أجهزة استشعار محمولة متصلة بنظام التحكم لماكينات الحفر تقوم بتسجيل جميع البيانات أثناء الحفر النفقى. استنادًا على المراجع العلمية المتعلقة بموضوع البحث، معدل اختراق ماكينة الحفر هو المعيار الأكثر أهمية الذي يمثل أدائية ماكينة الحفر والذي قد يختلف في الوحدة ليكون متر/ساعة أو مم/دورة. في هذه الدراسة، يتم عرض و تقييم اختيار المعاملات المؤثرة على معامل الاختراق عن طريق استخدام البيانات التى تم تسجيلها من عدد اثنين ماكينة حفر في مشروع أنفاق بورسعيد عن طريق معامل التحديد ومعامل ارتباط بيرسون بين جميع المتغيرات. وأخيرًا، أظهرت النتائج أن المعاملات المقترحة هي الأكثر تأثيرًا على أدائية ماكينة الحفر.

Abstract:

In modern tunneling projects, Tunnel Boring Machines “TBMs” are very often to be used instead of the traditional tunneling methods. TBMs have in general a circular cross-section with diameter conventionally varies from 1.0 m to 19.0 m depending on the tunnel usage, which can be small tunnel for underground water or sewer tunnel or big tunnel for roads, railway and subways.

Most of TBMs have many mounted monitoring sensors connected to TBM control system, to record all data measurements during tunneling. Based on literature, the TBM penetration rate is the most critical parameter representing the TBM performance, which may differ in the unit to be m/hr. or mm/rot. In this study, the selection of the parameters which affect the penetration rate are presented and evaluated while using the recorded data measurements from two TBMs in Port Said tunnels project based on the coefficient of determination (R^2) and Pearson-Correlation coefficient between all variables. Finally, the concluded results show that, the proposed parameters are the most ones affecting the TBM performance.

Keywords: TBM, Parameters, Performance, Penetration Rates

1. Introduction:

Studying the TBM Performance represents one of the most important approaches, by collecting and studying the data measurements of the TBMs and the soil characteristics in different projects. The TBM penetration rate is the most important parameter to study the TBM performance which may differ in the unit to be m/hr. or mm/rot (Salimi et al. 2016; Rispoli et al. 2017). The TBM penetration rate is generally affected by many parameters regarding the tunnel properties, TBM operating parameters and soil characteristics. The importance of these parameters should be evaluated to select the most significant parameters affecting the penetration rate. Many researchers have used the regression analysis to study, evaluate and select the most significant parameters affecting the penetration rates over the past years based on the coefficient of determination (R^2) between all variables (Yagiz et al. 2009; Khademi et al. 2010; Farrokh et al. 2012; Maher 2012; Delisio and Zhao 2014; Salimi et al. 2016).

Most researchers have studied the TBM performance in hard rock ground, (Maher 2012) studied the TBM performance in soft soils while using Earth Pressure Balance TBM. The most used parameters while studying the TBM performance in hard rock grounds are divided into three categories. The first category is related to the tunnel specifications such as depth (Benardos and Kaliampakos 2004). The second category is related to the hard rock properties such as core fracture frequency (CFF), uniaxial compressive strength (UCS), rock mass rating (RMR), rock quality designation (RQD), Brazilian tensile strength (BTS), brittle index (BI), distance between planes of weakness (DPW) and (α) alpha angle between plane of weakness and TBM direction of drive (Alvarez Grima et al. 2000; Benardos and Kaliampakos 2004; Yagiz et al. 2009; Khademi et al. 2010; Farrokh et al. 2012; Ghasemi et al. 2014; Co and Gokceoglu 2017). The third category is related to the TBM operating parameters such as cutterhead rotations, disc cutter normal force, TBM thrust force and TBM operator experience (Farrokh et al. 2012; Armaghani et al. 2017). On the other hand, the used parameters while studying the TBM performance in soft soils are mainly related to the operating parameters such as cutterhead vertical offset, screw conveyor soil pressure, cutterhead temperature, grout component pressure, foam flow rate, foam pressure, TBM operator experience, etc. as reported by (Maher 2012)

In this study, the measured data of two Mix-shield TBMs are used to select and evaluate the parameters which affect the penetration rate while tunneling in soft soil conditions. These two Mix-shield TBMs with diameter 13.05 m were used to construct the two tunnels 19 km South of Port Said City in Egypt. The two tunnels are part of the Canal Region development plan aimed to contribute in North Sinai expansion by providing adequate linking infrastructure for trades between East and West (Figure 1). The tunneling process had been done from the East side of the canal to West side. The first TBM started in the North tunnel, then the second TBM followed in the South tunnel. The minimum observed distance between the two tunnels during the tunneling process was 150m.

Figure 1: Project Location

In this study, the factors which affect the penetration rate of the TBM are different from other projects based on the soil conditions, and the TBM type. Accordingly, and referring to literature, four categories of parameters have been selected as follows: tunnel specification, TBM operating parameters, soil characteristics and TBM operator experience.

2. Soil and TBM:

The soil profile found in Port Said tunnels project is divided into three layers as follows: clay layer 1 (very soft to medium clay), sand layer 2 (medium to dense silty sand) and clay layer 3 (very stiff to hard clay), as shown in Figure 2. The field measurements for sand layer 2 and clay layer 3 were limited.

On the other hand, as shown in Figure 2 there is intersection between sand layer 2 and clay layer 3 while clay layer 1 could be considered as a homogeneous layer without any interpolations. In addition as reported by (Rizos et al. 2018) high cutterhead clogging potentials had been found in the deeper part of clay layer 1. Accordingly, clay layer 1 has been considered the selected layer to be studied.

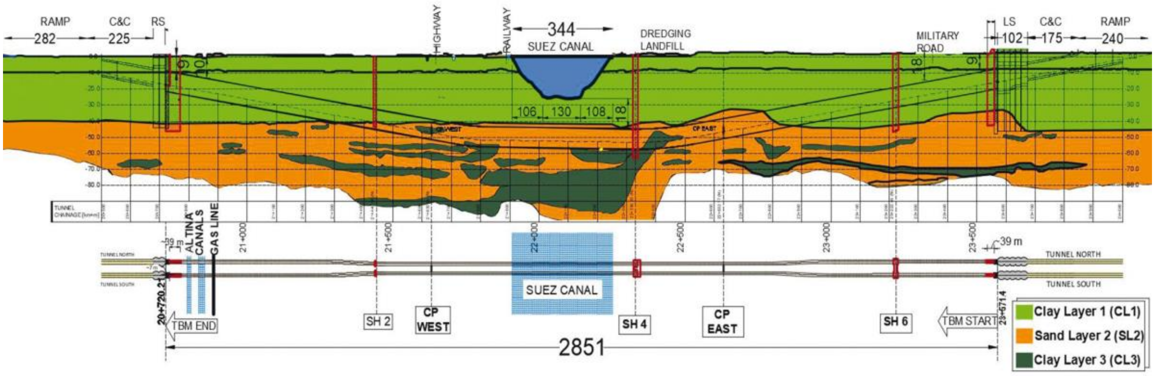

Figure 2: Soil Profile (Rizos et al. 2018)

The measured data for the tunnel specification, TBM and the soil characteristics had been filtered to the tunnel rings located in clay layer 1, which are the tunnel rings from 25 to 167 in the East side of the canal, and the tunnel rings from 1164 to 1390 in the West side of the canal.

The tunneling process in this project had been done using mix-shield TBM with separation treatment plant (STP) of maximum capacity 3200 m^3/hr. and compressed air station (Figure 3). In this case, some operating parameters had been selected related to the mix-shield TBM type such as: feed and slurry flows in (m^3/hr.) which were not used in the study by (Maher 2012) while using EPB machine with different operating parameters.

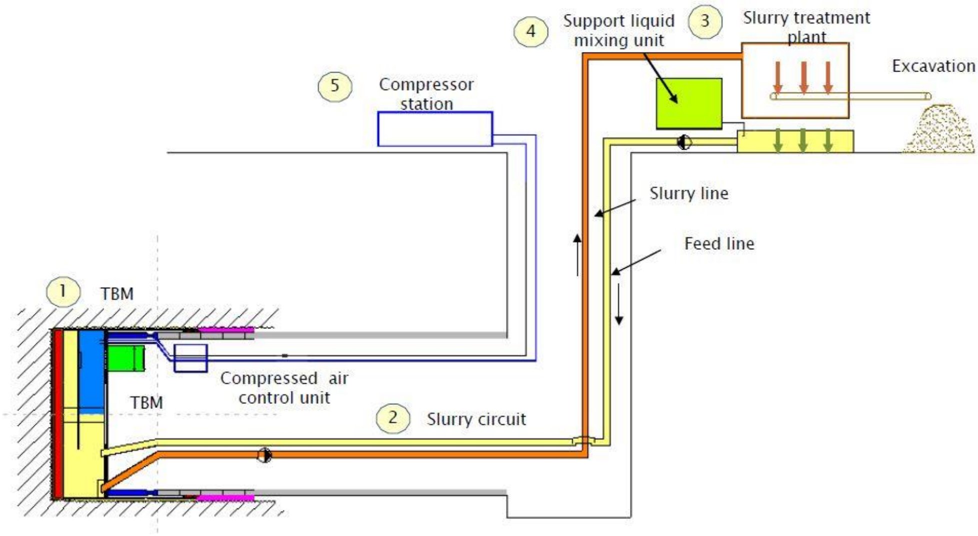

Figure 3: Mix-shield TBM

3. Parameters Selection:

In this study, the parameters which affect the TBM penetration rate have been divided into 4 categories as follows: tunnel specification, TBM operating parameters, soil characteristics, and TBM operator experience.

Table 1: Parameters Categories

Category 1	Category 2	Category 3	Category 4
Tunnel depth	Face Pressure	Clay Content	TBM Operator Experience
Slope	Air Bubble Pressure	Silt Content	
	Cutterhead Speed	Plastic Limit	
	Total Thrust Force	Bulk Density	
	Feed Flow	Liquidity Index	
	Slurry Flow	Undrained Shear Strength	
	Average Grout Pressure		

Referring to literature, the operating parameters which affect the TBM penetration rate in soft soils are different from those used in hard rock grounds, as in the soft soil projects are focusing on balancing the face pressure, and easily removing the excavated materials from the excavation chamber (Maher 2012). Consequently, and based on the TBM operator experience in tunneling using mix-shield TBM, the most important operating parameters affecting the penetration rates to maintain the tunnel face and controlling TBM performance are the face pressure, air bubble pressure, feed flow and slurry flow. In addition, the tail grout pressure could affect the penetration rate during tunneling based on the TBM operator experience as reported by (Maher 2012). In this case, the eight lines of tail grout of the mix-shield TBM in Port Said project had been averaged to one value per each tunnel ring. Furthermore, the effect of the cutterhead speed, and the total thrust force during tunneling were significant, as the more thrust force the more penetration occurs while the more cutterhead rotation the less penetration occurs.

The recorded data measurements are smoothed to be over each tunnel ring not every 10 seconds, as the TBM records the measurements each 10 seconds. In some cases, the influence of some parameters on the penetration rate could only be observed by the TBM. For example, the grout pressure has an effect on the penetration rate while starting the injection process; so that in some cases and after long stop of the TBM the tail grout injection pressure could be used to push the TBM forward which is directly affecting the penetration rate. Accordingly, the TBM operator experience has a great influence during the selection of the parameters which affect the penetration rate.

On the other hand, the selection of the soil parameters had been done based on the available field measurements in Port Said project. In addition, as no reference was found in literature regarding the most affecting parameters on the penetration rate in the clay soils; the selection had been done based on the most important and critical parameters representing the clay layer. In addition, the undrained shear strength has been selected as the tunneling process is done in undrained condition since, the time of tunneling is too short to maintain the drained condition.

Accordingly, and as outlined in Table 1, the selected parameters in this study are tunnel depth (m), tunnel slope, face pressure (bar), air bubble pressure (bar), cutterhead speed (rpm), total thrust force (kN), feed flow (m^3/hr.), slurry flow (m^3/hr.), average grout pressure (bar), clay content (%), silt content (%), plastic limit (%), bulk density (kN/m^3), liquidity index (%) and undrained shear strength (kN/m^2).

4. Parameters Evaluation:

After selecting the parameters, the evaluation process was assessed to assure that these parameters are significantly affecting the mix-shield TBM penetration rate. In that case, two approaches have been considered to measure the correlations between the parameters as follows:

4.1 <u>Coefficient of Determination (R^2):</u>

Coefficient of Determination (R^2) = $$\frac{S_{xy}^2}{S_{xx}S_{yy}} \quad (1)$$

Where, $$S_{xx} = \sum_{i=1}^{n} x_i^2 - \left(\frac{1}{n}\right)\left(\sum_{i=1}^{n} x_i\right)^2 \quad (2)$$

$$S_{yy} = \sum_{i=1}^{n} y_i^2 - \left(\frac{1}{n}\right)\left(\sum_{i=1}^{n} y_i\right)^2 \quad (3)$$

$$S_{xy} = \sum_{i=1}^{n} x_i y_i - \left(\frac{1}{n}\right)\left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right) \quad (4)$$

Where X and Y are two different variables

While using the coefficient of determination (R^2) to measure and evaluate the correlation between the parameters, the graphical representation should be provided with the R^2 values, as the values have always positive sign even if the relationship between the parameters is positively or negatively correlated.

Some input parameters have a direct effect on the penetration rate, while other parameters have an indirect effect. For example, the clay content has a good correlation with the depth, while the depth has a correlation directly with the penetration rate.

4.2 Pearson-Correlation Coefficient:

$$\text{Pearson-correlation coefficient (PCC)} = \frac{N\sum xy - (\sum x)(\sum y)}{\sqrt{\{N\sum x^2 - (\sum x)^2\}\{N\sum y^2 - (\sum y)^2\}}}$$

Where X and Y are two different variables

Pearson-correlation coefficients could be used to measure and evaluate the correlation between the parameters better than the correlation of determination (R^2) as the coefficient value can range between -1.00 and +1.00. Accordingly, if the coefficient value has a negative sign that means the relationship between the variables are negatively correlated (inverse relationship). Also, If the coefficient value has a positive sign that means the relationship between the variables are positively correlated (direct relationship). In that case, there is no need to provide the graphical representation with the calculated values of Pearson-correlation coefficients, as the calculated values could represent the correlation direction by the sign mean.

5. Results:

5.1 Coefficient of Determination (R^2):

The graphical representations between all parameters have been drawn and the coefficients of determination (R^2) have been calculated to check the most influencing parameters on the penetration rate. Figure 4 and Figure 5 show the coefficients of determination (R^2) between all parameters in the upward and downward slopes.

Accordingly, there are some parameters which directly affect the penetration rate such as the cutterhead Speed, depth and thrust force, while other parameters have an indirect effect on the penetration rate such as average grout pressure, plastic limit and clay content.

North Tunnel																														
	Penetration Rate		Depth		Face Pressure		Air Bubble Pressure		Cutterhead Speed		Total Thrust Force		Feed Flow		Slurry Flow		Average Grout Pressure		Clay Content		Silt Content		Plastic Limit		Bulk Density		Liquidity Index		Undrained Shear Strength	
	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up
Penetration Rate	1.0000	1.0000																												
Depth	0.0115	0.1668	1.0000	1.0000																										
Face Pressure	0.0224	0.1398	0.8713	0.9746	1.0000	1.0000																								
Air Bubble Pressure	0.1232	0.1476	0.6526	0.9799	0.7561	0.9924	1.0000	1.0000																						
Cutterhead Speed	0.6919	0.7069	0.0247	0.0794	0.0141	0.0735	0.0166	0.0783	1.0000	1.0000																				
Total Thrust Force	0.0349	0.1637	0.8577	0.9759	0.9424	0.9880	0.6974	0.9915	0.0059	0.0937	1.0000	1.0000																		
Feed Flow	0.0048	0.1556	0.0620	0.1976	0.0459	0.2185	0.0145	0.2068	0.0158	0.2293	0.0681	0.2173	1.0000	1.0000																
Slurry Flow	0.0145	0.0790	0.1768	0.2655	0.1337	0.2745	0.0356	0.2766	0.0791	0.1036	0.1403	0.2755	0.2018	0.2822	1.0000	1.0000														
Average Grout Pressure	0.0461	0.2758	0.6723	0.8012	0.7266	0.8051	0.7181	0.8027	0.0001	0.1847	0.6041	0.8101	0.0328	0.2523	0.0783	0.2738	1.0000	1.0000												
Clay Content	0.0012	0.2914	0.6803	0.3989	0.4148	0.4321	0.2296	0.4302	0.0663	0.2822	0.4380	0.4593	0.0472	0.3288	0.1756	0.2198	0.2865	0.4783	1.0000	1.0000										
Silt Content	0.0860	0.0461	0.0015	0.1165	0.0052	0.1552	0.1132	0.1482	0.1404	0.0421	0.0012	0.1574	0.0102	0.1139	0.0370	0.1005	0.0479	0.1500	0.5217	0.2488	1.0000	1.0000								
Plastic Limit	0.0016	0.2212	0.7278	0.8100	0.4397	0.8266	0.3703	0.8239	0.0226	0.1429	0.4432	0.8418	0.0336	0.2704	0.1348	0.2818	0.3940	0.7430	0.8914	0.7526	0.0493	0.4319	1.0000	1.0000						
Bulk Density	0.0439	0.0004	0.0731	0.8523	0.8411	0.1159	0.5886	0.1165	0.0039	0.0131	0.8611	0.1158	0.0560	0.0403	0.1589	0.0781	0.5884	0.0816	0.4116	0.1070	0.0102	0.3867	0.4216	0.1304	1.0000	1.0000				
Liquidity Index	0.0040	0.0002	0.7469	0.0002	0.4915	0.0044	0.4035	0.0030	0.0204	0.0008	0.4822	0.0041	0.0443	0.0147	0.1249	0.0179	0.4318	0.0043	0.8978	0.1493	0.0800	0.8134	0.9520	0.1066	0.4288	0.3822	1.0000	1.0000		
Undrained Shear Strength	0.0115	0.1668	1.0000	1.0000	0.8713	0.9746	0.6526	0.9799	0.0247	0.0794	0.8577	0.9759	0.0620	0.1976	0.1768	0.2655	0.6732	0.8012	0.6803	0.3989	0.0015	0.1165	0.7278	0.8100	0.8523	0.0731	0.7469	0.0002	1.0000	1.0000

Figure 4: Coefficients of Determination (R^2) for the North Tunnel

South Tunnel																														
	Penetration Rate		Depth		Face Pressure		Air Bubble Pressure		Cutterhead Speed		Total Thrust Force		Feed Flow		Slurry Flow		Average Grout Pressure		Clay Content		Silt Content		Plastic Limit		Bulk Density		Liquidity Index		Undrained Shear Strength	
	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up
Penetration Rate	1.0000	1.0000																												
Depth	0.1172	0.5156	1.0000	1.0000																										
Face Pressure	0.2277	0.5164	0.9295	0.9830	1.0000	1.0000																								
Air Bubble Pressure	0.2182	0.5138	0.9346	0.9835	0.9965	0.9984	1.0000	1.0000																						
Cutterhead Speed	0.6742	0.7267	0.0267	0.2668	0.0876	0.2690	0.0777	0.2648	1.0000	1.0000																				
Total Thrust Force	0.2593	0.5064	0.8969	0.9826	0.9675	0.9947	0.9690	0.9951	0.0980	0.2610	1.0000	1.0000																		
Feed Flow	0.0020	0.0407	0.0002	0.0239	0.0006	0.0172	0.0009	0.0180	0.0100	0.0120	0.0006	0.0172	1.0000	1.0000																
Slurry Flow	0.0013	0.0264	0.0276	0.0432	0.0295	0.0388	0.0260	0.0386	0.0237	0.0078	0.0247	0.0360	0.1995	0.0680	1.0000	1.0000														
Average Grout Pressure	0.1982	0.4824	0.6218	0.7199	0.6582	0.7331	0.6570	0.7255	0.0720	0.2994	0.6315	0.7183	0.0070	0.0159	0.0090	0.0352	1.0000	1.0000												
Clay Content	0.0163	0.2127	0.6254	0.3989	0.4477	0.4559	0.4598	0.4625	0.0046	0.0752	0.4314	0.4435	0.0052	0.0011	0.0097	0.0261	0.3019	0.2595	1.0000	1.0000										
Silt Content	0.1894	0.1021	0.0051	0.1140	0.0080	0.1505	0.0070	0.1532	0.0918	0.0516	0.0209	0.1314	0.0018	0.0109	0.0508	0.0174	0.0251	0.0943	0.5217	0.2488	1.0000	1.0000								
Plastic Limit	0.0762	0.4478	0.6224	0.8087	0.4939	0.8398	0.5095	0.8435	0.1000	0.2138	0.5148	0.8187	0.0187	0.0054	0.0003	0.0490	0.3668	0.5672	0.8914	0.7526	0.0500	0.4319	1.0000	1.0000						
Bulk Density	0.1564	0.0830	0.8690	0.0710	0.8571	0.1045	0.8478	0.1060	0.0557	0.0581	0.8280	0.1008	0.0014	0.0011	0.0257	0.0020	0.6476	0.1078	0.4116	0.1070	0.0100	0.3867	0.4216	0.1304	1.0000	1.0000				
Liquidity Index	0.0527	0.0061	0.6762	0.1100	0.5275	0.0028	0.5460	0.0033	0.0004	0.0050	0.5470	0.0006	0.0067	0.0026	0.0013	0.0058	0.3675	0.0011	0.8978	0.1493	0.2000	0.8134	0.9520	0.1066	0.4288	0.3822	1.0000	1.0000		
Undrained Shear Strength	0.1172	0.5156	1.0000	1.0000	0.9295	0.9830	0.9346	0.9835	0.0267	0.2668	0.8969	0.9826	0.0002	0.0239	0.0276	0.0432	0.6218	0.7199	0.6254	0.4004	0.0051	0.1140	0.6224	0.8087	0.8690	0.1000	0.6762	0.1000	1.0000	1.0000

Figure 5: Coefficients of Determination (R^2) for the South Tunnel

5.2 Pearson-Correlation Coefficient:

Figure 6 and Figure 7 illustrate the Pearson-correlation coefficients between all parameters in the upward and downward slopes. Studying the downward slopes in both tunnels, all input parameters are inversely proportional to the penetration rate except the clay content and the liquidity index in the North tunnel, while all input parameters are directly proportional to the penetration rate except cutterhead speed, slurry flow and liquidity index in the South tunnel.

Studying the upward slopes, all input parameters are directly proportional to the penetration rate except cutterhead speed, feed and slurry flows, silt content and liquidity index in the North tunnel. While all input parameters are inversely proportional to the penetration rate except slurry flow, silt content, liquidity index cutterhead speed, slurry flow and liquidity index in the South tunnel. Accordingly, the calculated values of Pearson-correlation coefficients for all parameters in North and South tunnels indicate that, all input parameters have a significant effect on the penetration rate (Pearson-correlation ≥ 0.1) as shown in Figure 6 and Figure 7

North Tunnel																														
	Penetration Rate		Depth		Face Pressure		Air Bubble Pressure		Cutterhead Speed		Total Thrust Force		Feed Flow		Slurry Flow		Average Grout Pressure		Clay Content		Silt Content		Plastic Limit		Bulk Density		Liquidity Index		Undrained Shear Strength	
	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up
Penetration Rate	1.0000	1.0000																												
Depth	-0.107	0.408	1.0000	1.0000																										
Face Pressure	-0.150	0.374	0.933	0.987	1.0000	1.0000																								
Air Bubble Pressure	-0.351	0.384	0.808	0.990	0.870	0.996	1.0000	1.0000																						
Cutterhead Speed	-0.832	-0.841	-0.157	-0.282	-0.119	-0.271	0.129	-0.280	1.0000	1.0000																				
Total Thrust Force	-0.187	0.405	0.926	0.988	0.971	0.994	0.835	0.996	-0.077	-0.306	1.0000	1.0000																		
Feed Flow	-0.069	-0.394	-0.249	-0.445	-0.214	-0.467	-0.120	-0.455	0.126	0.479	-0.261	-0.466	1.0000	1.0000																
Slurry Flow	-0.120	-0.281	-0.421	-0.515	-0.366	-0.524	-0.189	-0.526	0.281	0.322	-0.375	-0.525	0.449	0.531	1.0000	1.0000														
Average Grout Pressure	-0.215	0.525	0.821	0.895	0.852	0.897	0.847	0.896	-0.012	-0.430	0.777	0.900	-0.181	-0.502	-0.2800	-0.523	1.0000	1.0000												
Clay Content	0.034	0.540	0.825	0.632	0.644	0.657	0.479	0.656	-0.257	-0.531	0.662	0.678	-0.217	-0.573	-0.419	-0.469	0.535	0.692	1.0000	1.0000										
Silt Content	-0.293	-0.215	-0.038	-0.341	0.072	-0.394	0.336	-0.385	0.375	0.205	0.035	-0.397	0.101	0.337	0.192	0.317	0.219	-0.387	-0.499	-0.722	1.0000	1.0000								
Plastic Limit	-0.040	0.470	0.853	0.900	0.663	0.909	0.609	0.908	-0.150	-0.378	0.666	0.917	-0.183	-0.520	-0.367	-0.531	0.628	0.862	0.944	0.868	-0.222	-0.657	1.0000	1.0000						
Bulk Density	-0.209	0.020	0.923	0.270	0.917	0.340	0.767	0.341	-0.062	-0.114	0.928	0.340	-0.237	-0.201	-0.399	-0.279	0.767	0.286	0.642	0.327	0.101	-0.622	0.649	0.361	1.0000	1.0000				
Liquidity Index	0.063	-0.016	-0.864	-0.015	-0.701	-0.066	-0.635	-0.055	0.143	0.029	-0.694	-0.064	0.210	0.121	0.353	0.134	-0.657	-0.065	-0.948	-0.386	0.283	0.902	-0.976	-0.327	-0.6550	-0.618	1.0000	1.0000		
Undrained Shear Strength	-0.107	0.408	1.0000	1.000	0.933	0.987	0.808	0.990	-0.157	-0.282	0.926	0.988	-0.249	-0.445	-0.421	-0.515	0.821	0.895	0.825	0.632	-0.038	-0.341	0.853	0.900	0.9230	0.270	-0.8640	-0.015	1.0000	1.0000

Figure 6: Pearson-Correlation Coefficients for the North Tunnel

	South Tunnel																													
	Penetration Rate		Depth		Face Pressure		Air Bubble Pressure		Cutterhead Speed		Total Thrust Force		Feed Flow		Slurry Flow		Average Grout Pressure		Clay Content		Silt Content		Plastic Limit		Bulk Density		Liquidity Index		Undrained Shear Strength	
	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up
Penetration Rate	1.0000	1.0000																												
Depth	0.342	-0.718	1.0000	1.0000																										
Face Pressure	0.477	-0.719	0.964	0.991	1.0000	1.0000																								
Air Bubble Pressure	0.467	-0.717	0.967	0.992	0.998	0.999	1.0000	1.0000																						
Cutterhead Speed	-0.821	-0.852	-0.163	0.517	-0.296	0.519	-0.279	0.515	1.0000	1.0000																				
Total Thrust Force	0.509	-0.712	0.947	0.991	0.984	0.997	0.984	0.998	-0.313	0.511	1.0000	1.0000																		
Feed Flow	0.045	-0.202	0.014	0.154	0.024	0.131	0.030	0.134	-0.007	0.110	0.025	0.131	1.0000	1.0000																
Slurry Flow	-0.037	0.162	-0.166	-0.208	-0.172	-0.197	-0.161	-0.196	0.154	-0.088	-0.157	-0.190	0.447	0.261	1.0000	1.0000														
Average Grout Pressure	0.445	-0.695	0.789	0.848	0.811	0.856	0.811	0.852	-0.268	0.547	0.795	0.848	0.084	0.126	-0.001	-0.188	1.0000	1.0000												
Clay Content	0.128	-0.461	0.791	0.633	0.669	0.675	0.678	0.680	0.068	0.274	0.657	0.666	0.072	-0.033	-0.099	-0.162	0.549	0.509	1.0000	1.0000										
Silt Content	0.435	0.320	-0.072	-0.338	0.089	-0.388	0.084	-0.391	-0.303	-0.227	0.145	-0.362	0.104	0.042	0.225	0.132	0.158	-0.307	-0.499	-0.722	1.0000	1.0000								
Plastic Limit	0.276	-0.669	0.789	0.899	0.703	0.916	0.714	0.918	0.010	0.462	0.717	0.905	0.137	0.074	0.018	-0.221	0.606	0.753	0.944	0.868	-0.222	-0.657	1.0000	1.0000						
Bulk Density	0.396	-0.288	0.932	0.267	0.926	0.323	0.921	0.326	-0.236	0.241	0.910	0.318	0.037	0.001	-0.160	-0.044	0.805	0.328	0.642	0.327	0.101	-0.622	0.649	0.361	1.0000	1.0000				
Liquidity Index	-0.229	0.078	-0.822	-0.010	-0.726	-0.053	-0.739	-0.057	-0.020	-0.071	-0.740	-0.025	-0.082	0.051	0.035	0.076	-0.606	-0.033	-0.948	-0.386	0.283	0.902	-0.976	-0.327	-0.655	-0.618	1.0000	1.0000		
Undrained Shear Strength	0.342	-0.718	1.000	1.0000	0.964	0.991	0.967	0.992	-0.163	0.517	0.947	0.991	0.014	0.154	-0.166	-0.208	0.789	0.848	0.791	0.633	-0.072	-0.338	0.789	0.899	0.932	0.267	-0.822	-0.010	1.0000	1.0000

Figure 7: Pearson-Correlation Coefficients for the South Tunnel

In that case, it can be concluded that all independent variables (input parameters) have a significant effect on the penetration rate value (output parameter), and should be used while developing the performance prediction models of the mix-shield TBM type.

6. Summary and Conclusions:

The selected parameters in this study have been classified into four categories based on the soil conditions and the mix-shield TBM type as follows: tunnel specification, TBM operating parameters, soil characteristics and TBM operator experience.

The following pointed the main conclusions of this study:

1. The selected parameters in this study are representing the mix-shield TBM type and the clay soil properties.
2. The use of Pearson-correlation coefficient is better than the coefficient of determination (R^2) in evaluating, measuring the correlations between all parameters and selecting the most significant parameters which affect the penetration rate
3. There are sufficient correlations between all input parameters and the penetration rate and should be used for developing the performance prediction models.

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