Analysis of Shield Tunneling Parameters and Research on Prediction Model of Tunneling Excavation Speed in Volcanic Ash Strata of Jakarta–Bandung High-Speed Railway Project

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Abstract: Insufficient investigations have been conducted on the analysis of shield tunneling parameters and the prediction of the tunneling excavation speed in formations composed of volcanic ash strata. To address this issue, we employ a comprehensive approach utilizing literature research, mathematical statistics, and other methodologies, centered on the analysis of the No. 1 Tunnel of the Jakarta–Bandung High-Speed Railway. Our focus is on examining the evolution patterns and inter-relationships of shield tunneling parameters within volcanic ash strata. Subsequently, we propose an optimized strategy for these tunneling parameters. By employing six machine-learning algorithms to construct prediction models, we compare and analyze their performance in predicting the tunneling excavation speed. The results indicate a positive correlation between slurry pressure and tunnel depth in volcanic ash strata, suggesting that the grouting pressure should exceed the slurry pressure by approximately 0.22 MPa. In the composite stratum of “volcanic ash debris + round gravel”, the cutter torque exhibits a strong negative correlation with the total thrust (−0.77). Due to tool wear and ground resistance, the excavation speed and cutter speed are weakly negatively correlated. Compared to other strata, shield tunneling in volcanic ash strata exhibits larger grouting pressure fluctuations, slower tunneling excavation speed, greater total thrust, higher cutter torque, and lower cutter speed. Regarding shield tunneling excavation speed prediction, the ranking of the algorithm performance is RF > DNN > ANN > BPNN > MNR > SVM, with RF achieving a decision coefficient of 0.829. The RF model is well-suited for predicting the shield structure tunneling excavation speed.

Keywords: tunnel engineering; excavation parameters; volcanic ash strata; optimization; random forest

1. Introduction

With the rapid advancement of tunnel construction technology, shield construction has gained widespread adoption due to its merits, including high efficiency, minimal environmental impact, and robust adaptability [1,2]. The key factors influencing shield propulsion, known as the shield tunneling parameters, encompass the slurry pressure, soil pressure, cutter torque, cutter speed, excavation speed, and various torque-related indicators. The multitude of tunneling parameters exhibit varying degrees of correlation influenced by environmental factors and human operations [3]. Establishing judicious shield tunneling parameters effectively addresses challenges such as mud cake formation, tool wear, and mud stagnation during the tunneling process [4–6]. Given the plethora of tunneling parameters, the selection of crucial parameters, analysis of their fundamental behaviors, and understanding the distribution patterns under diverse environmental conditions are pivotal aspects of tunneling parameter analysis. Furthermore, predicting the shield tunneling excavation speed holds paramount importance in tunnel construction.
Such predictions offer scientifically grounded references for the tunneling excavation speed during engineering projects, ensuring quality, enhancing construction efficiency, and mitigating engineering risks and costs. Currently, scholars have delved into the analysis of shield tunneling parameters and the forecasting of the tunneling excavation speed.

Several scholars have engaged in pertinent research concerning shield machine tunneling parameters. Theoretical exploration primarily involves deriving expressions that link shield tunneling parameters, such as employing the shield thrust, cutter torque, and excavation speed to predict the surface settlement [7–9]. Statistical analyses have been conducted on tunneling parameters during shield tunneling, revealing variations across different strata [10,11]. Scholars have scrutinized the sensitivity of shield tunneling to diverse parameter alterations and subsequently optimized shield machine tunneling parameters [12,13]. In the realm of numerical simulation, scholars have employed finite element calculation models to investigate shield tunneling parameters in different strata or analyze the impact of varied tunneling parameters on the surface settlement and tunneling excavation speed [14].

In shield machine tunneling, a substantial volume of measured data are typically generated for tunneling parameters. Predicting the shield machine tunneling excavation speed involves addressing the challenge of multivariate time series regression [15]. Machine-learning algorithms, including the Multiple Linear Regression [16,17] (MNR), Random Forest [18,19] (RF), Backpropagation Neural Network [20,21] (BPNN), Deep Neural Network [22,23] (DNN), Support Vector Machine [24] (SVM), and other algorithms, demonstrate notable advantages in processing time series data. The prediction of the shield tunneling excavation speed is achieved through the implementation of artificial intelligence prediction models. Numerous research outcomes indicate that artificial intelligence models exhibit superior prediction performance compared to empirical models.

Extensive research has been conducted on shield tunneling parameters. Volcanic ash strata exhibit unique cementing features, shear strength, and deformation/settlement properties that significantly differ from other strata, impacting the safety of shield tunneling construction [25–27]. However, a notable gap remains in the scholarly examination of parameter analysis and the prediction of the tunneling excavation speed pertaining to mud shield tunneling within volcanic ash strata. This paper focuses on the No. 1 Tunnel of the Jakarta–Bandung High-Speed Railway. Using mathematical statistical analysis, this study examines the variation patterns of shield tunneling parameters and their inter-relationships within volcanic ash strata. Additionally, a machine-learning algorithm prediction model is established. The paper compares and analyzes the prediction performance of six algorithms (ANN, DNN, BPNN, SVM, MNR, and RF) in terms of the tunneling excavation speed.

2. Engineering Background

2.1. Engineering Overview

Tunnel No. 1 of the Jakarta–Bandung High-Speed Railway spans from DK2 + 540.0 to DK4 + 410.0, covering a total length of 1885 m, with a maximum depth of approximately 36 m (see Figure 1 for details). This single-hole, two-lane tunnel has a shield range extending from DK2 + 771.5 to DK4 + 238.5, and the inner track is situated at a depth ranging from 5.0 to 24.0 m. The tunnel’s geological composition includes clay, volcanic ash-cemented gravel, sandy soil, and fine soil. The construction presents challenges due to the complex conditions, high difficulty, and associated risks. The geological features involve a high water table, abundant surface water, and passage through volcanic accumulation layers with fragmented rock, low slurry stone strength, and significant weathering and cementation effects. Moreover, the tunnel intersects densely populated areas with buildings, highways, and interchange ramps, and it passes adjacent to two mosques. To tackle the intricate geological challenges and risks in Tunnel No. 1, the first oversized diameter slurry-water balanced shield machine developed by China High-Speed Railway Overseas is employed—a pioneering technology in Southeast Asia. This shield machine boasts a cutter diameter of 13.19 m, a length of approximately 101 m, and a weight exceeding 2600 tons. The cutter
tool arrangement is depicted in Figure 2. The chosen lining method involves assembled reinforced concrete pipe sheets combined with box culverts. The pipe sheets use universal pipe sheet rings, with a lining ring width of 2000 mm, inner diameter of 11,700 m, outer diameter of 12,800 mm, and a thickness of 550 mm.

Figure 1. Plan line diagram of Tunnel No. 1.

Figure 2. Cutterhead layout of the slurry shield.

2.2. Geological Situation

The tunnel traverses mainly Quaternary Holocene artificial accumulation layers, characterized by miscellaneous fill. The primary strata consist of Quaternary Pleistocene Alluvial Layer, including clay, silty clay, sandy soil, and fine round gravel soil. Some areas exhibit cementation, resulting in high hardness and strength. Geological exploration data indicate the shield machine encounters three distinct strata, as illustrated in Figure 3 and detailed in Table 1. Volcanic ash strata round gravel is shown in Figure 4.

Figure 3. Strata schematic diagram of shield tunneling.
Table 1. Strata classification of the shield interval.

<table>
<thead>
<tr>
<th>Stratum Serial Number</th>
<th>Name of Strata</th>
<th>Rock and Soil Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>“volcanic ash debris + round gravel” composite strata</td>
<td>Fine sand, fine round gravel soil</td>
</tr>
<tr>
<td>II</td>
<td>“clay + volcanic ash debris” composite strata</td>
<td>Clay, silty clay, silty sand, fine sand</td>
</tr>
<tr>
<td>III</td>
<td>“clay + volcanic ash debris + round gravel” composite strata</td>
<td>Clay, silty clay, silty sand, fine sand, fine round gravel soil</td>
</tr>
</tbody>
</table>

Figure 4. Volcanic ash strata round gravel.

2.3. Hydrology Situation

(1) Surface Water
The site’s surface water primarily comprises river water and stagnant water in low-lying areas. The majority of the rivers are perennial, exhibiting seasonal changes in the water levels. Between DK2 + 540.0 and DK2 + 600.0, there are parallel rivers with concrete lining on both sides. These rivers are approximately 18 m wide, with water depths ranging from 0.5 to 1.5 m. The water flow is slow, and the river banks are straight. In the dry season, the water depth is less than 1 m, while it increases during the rainy season.

(2) Groundwater
The groundwater at the site primarily consists of Quaternary pore phreatic water and confined water. Pore phreatic water is mainly replenished by atmospheric precipitation, with a depth of 0.3 to 7.8 m and a water level generally ranging from 2 to 3 m. The first layer of confined water is beneath a relatively impermeable roof composed of clay, silty clay, and other clay layers, with a roof burial depth of about 10.0 to 21.3 m and an impermeable floor burial depth of about 18.1 to 34.7 m. This confined water primarily occurs in silt, fine sand, and fine round gravel soil. The second layer of confined water also has a relatively impermeable roof, with clay, silty clay, and other clay layers, featuring a roof burial depth of about 37.5 to 48.7 m and an impermeable floor burial depth of about 40.6 to 50.0 m. The confined water in this layer mainly occurs in silty and fine sand.

2.4. Engineering Characteristics of Volcanic Ash Strata
Volcanic ash strata refer to a layer of soil or rock formed by volcanic ash and pyroclastic materials, shaped by geological processes.

(1) Cementing Feature
The cementing material within the volcanic ash strata undergoes vibrations and cutting during shield tunneling, influencing the overall stratum stability [28].

(2) Shear Strength and Stability
The shear strength of volcanic ash formations is influenced by the cementing material. In shield tunneling, soil shear strength directly impacts the cutterhead’s cutting ability and the stability of the entire shield working face [29].

(3) Soil Deformation and Settlement
Shield tunneling in volcanic ash strata is prone to significant deformation and settlement, posing challenges during the construction process.

3. Analysis of Shield Tunneling Parameters

To ensure the representativeness and accuracy of tunneling parameter research, it is crucial to assess whether the selected parameters adequately capture the characteristics of shield tunneling in tandem with the strata properties. Additionally, the chosen parameters should comprehensively reflect the variations in shield tunneling. Tailored to the project’s specifics, the key parameters for statistical analysis include the average values of the slurry pressure, grouting pressure, grouting amount, un earthed amount, total thrust, cutter torque, cutter speed, and excavation speed.

During the tunneling process, the shield recorded 36 data items every 5 s, accumulating approximately 7.19 million data points. Focusing on the on-site excavation conditions, the study concentrates on rings 56 to 730 as the primary research objects. This meticulous selection ensures a robust examination of the tunneling dynamics within the specific context of the project.

3.1. Slurry Pressure

The correlation between the slurry pressure and the shield tunnel ring number is illustrated in Figure 5. Table 2 presents the statistical characteristics of the slurry pressure across three distinct stratum conditions.

![Figure 5. The curve of the slurry pressure changing with the ring number.](image)

**Table 2.** Statistical characteristics of different strata with the slurry pressure.

<table>
<thead>
<tr>
<th>Stratum Serial Number</th>
<th>Mean Value</th>
<th>Standard Deviation</th>
<th>Median</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.165</td>
<td>0.006</td>
<td>0.166</td>
<td>0.154</td>
<td>0.179</td>
<td>-0.251</td>
</tr>
<tr>
<td>II</td>
<td>0.215</td>
<td>0.023</td>
<td>0.212</td>
<td>0.170</td>
<td>0.262</td>
<td>0.332</td>
</tr>
<tr>
<td>III</td>
<td>0.135</td>
<td>0.025</td>
<td>0.140</td>
<td>0.076</td>
<td>0.175</td>
<td>-0.202</td>
</tr>
</tbody>
</table>

Analysis of Figure 5 and Table 2 reveals that the slurry pressure shows minimal correlation with the stratum and is predominantly linked to the tunnel burial depth. The slurry pressure during shield tunneling undergoes three distinct stages. (1) Rapid Growth Stage (56–251 rings): Slurry pressure increased swiftly from 0.139 MPa to 0.238 MPa, with a growth rate of 0.0005 MPa/ring. This surge is attributed to the shallow launching of the shield machine, leading to an initially low slurry pressure. As the machine’s burial depth increases, the slurry pressure rises rapidly. (2) Fluctuation Growth Stage (252–318 rings): Slurry pressure decreased from 0.238 MPa at 251 rings to 0.195 MPa and then experienced a rapid increase. This fluctuation is tied to a decrease in the slurry pressure when the shield tunneling approaches residential areas. (3) Rapid Decline Stage (319–730 rings): Slurry pres-
sure declined sharply from 0.280 MPa to 0.076 MPa, with a decline rate of 0.0005 MPa/ring. As the shield tunnels, the burial depth of the intermediate shield decreases, bringing the shield closer to the receiving mileage.

3.2. Grouting Pressure

The correlation between the grouting pressure and the shield tunnel ring number is illustrated in Figure 6. Table 3 presents the statistical characteristics of the grouting pressure across three distinct stratum conditions.

![Figure 6](image_url)

**Figure 6.** The curve of the grouting pressure changing with the ring number.

<table>
<thead>
<tr>
<th>Stratum Serial Number</th>
<th>Mean Value</th>
<th>Standard Deviation</th>
<th>Median</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.397</td>
<td>0.034</td>
<td>0.396</td>
<td>0.340</td>
<td>0.464</td>
<td>0.244</td>
</tr>
<tr>
<td>II</td>
<td>0.416</td>
<td>0.053</td>
<td>0.432</td>
<td>0.301</td>
<td>0.522</td>
<td>-0.306</td>
</tr>
<tr>
<td>III</td>
<td>0.384</td>
<td>0.033</td>
<td>0.383</td>
<td>0.276</td>
<td>0.455</td>
<td>-0.852</td>
</tr>
</tbody>
</table>

Based on the analysis of Figure 6 and Table 3, it is evident that the grouting pressure exhibits substantial fluctuations. Notably, a sudden decrease in the grouting pressure at ring 286 is a deliberate adjustment during shield tunneling near the highway toll station and residential area. This adjustment aims to prevent local ground uplift caused by excessive grouting pressure. Conversely, a sudden increase in the grouting pressure at ring 460 results from artificial regulation to address ground subsidence. The grouting pressure concentrates within the range of 0.3 to 0.5 MPa, ensuring compactness between the segment and surrounding rock. Inadequate grouting pressure may lead to soil instability and significant deformation, while excessively high pressure can damage the segment structure or induce local ground uplift due to slurry channeling. Based on the analysis of Figure 7, it is evident that the mean value of the grouting pressure is 0.2−0.25 MPa larger than that of the slurry pressure. The grouting pressure consistently exceeds the slurry pressure by approximately 0.22 MPa.

In contrast to other strata [30,31], the grouting pressure in volcanic ash formations experiences significant fluctuations. This is attributed to the inherently high compressibility and inhomogeneity of volcanic ash strata, resulting in complex geological conditions. Urban areas, in particular, impose stringent criteria on ground subsidence and stratum deformation, making it challenging to control the grouting pressure during the shield tunneling process. Real-time adjustments are necessary based on the specific characteristics of the stratum.
Table 4. Statistical characteristics of different strata with the grouting amount.

<table>
<thead>
<tr>
<th>Stratum Serial Number</th>
<th>Mean Value</th>
<th>Standard Deviation</th>
<th>Median</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>18,641.8</td>
<td>1810.9</td>
<td>18,475</td>
<td>15,384</td>
<td>25,872</td>
<td>1.784</td>
</tr>
<tr>
<td>II</td>
<td>19,718.9</td>
<td>2088.8</td>
<td>19,404</td>
<td>15,504</td>
<td>32,952</td>
<td>2.097</td>
</tr>
<tr>
<td>III</td>
<td>19,429.7</td>
<td>2376.3</td>
<td>19,152</td>
<td>14,784</td>
<td>32,475</td>
<td>1.871</td>
</tr>
</tbody>
</table>

The analysis of Figure 8 and Table 4 reveals that, overall, the grouting amount remains relatively consistent across the different strata. It consistently fluctuates around the average value, and the grouting amounts for the three strata are comparable. Specifically, the grouting amount is consistently maintained within the range of 18,641.8 to 19,718.9 L.

3.4. Unearthed Amount

The correlation between the unearthed amount and the shield tunnel ring number is illustrated in Figure 9. Table 5 presents the statistical characteristics of the unearthed amount across three distinct stratum conditions.
Figure 9. The curve of the unearthed amount changing with the ring number.

Table 5. Statistical characteristics of different strata with the unearthed amount.

<table>
<thead>
<tr>
<th>Stratum Serial Number</th>
<th>Mean Value</th>
<th>Standard Deviation</th>
<th>Median</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>4.157</td>
<td>0.489</td>
<td>4.054</td>
<td>3.135</td>
<td>5.175</td>
<td>0.164</td>
</tr>
<tr>
<td>II</td>
<td>1.752</td>
<td>2.227</td>
<td>2.004</td>
<td>-4.811</td>
<td>5.887</td>
<td>-1.036</td>
</tr>
<tr>
<td>III</td>
<td>-2.631</td>
<td>2.965</td>
<td>-3.168</td>
<td>-8.577</td>
<td>5.010</td>
<td>0.579</td>
</tr>
</tbody>
</table>

Based on the analysis of Figure 9 and Table 5, it is evident that shield tunneling exhibits the highest unearthed amount in stratum I, controlled at approximately 4.157 t/min. This is mainly because stratum I has a shorter mileage, resulting in relatively concentrated statistical data. There is a declining trend in the unearthed amount in stratum II, with most of the unearthed amount concentrated between 0 and 4 t/min, representing a 57.6% decrease compared to stratum I. This decline can be attributed to the stratum’s proximity to a residential area. Additionally, as the excavation approaches stratum III, there is a rapid decrease, reaching a minimum of −4.811 t/min. In stratum III, the unearthed amount fluctuates significantly with the ring number, primarily concentrating between −6 and −1 t/min. The average unearthed amount is −2.631 t/min. Due to the stratum’s proximity to a residential area and the susceptibility of the tunnel face to instability, the amount of mud sent exceeds the amount discharged, resulting in a negative unearthed amount. This strategy is employed to maintain the tunnel face stability and prevent ground collapse.

3.5. Total Thrust

The correlation between the total thrust and the shield tunnel ring number is illustrated in Figure 10. Table 6 presents the statistical characteristics of the total thrust across three distinct stratum conditions.

Table 6. Statistical characteristics of different strata with the total thrust.

<table>
<thead>
<tr>
<th>Stratum Serial Number</th>
<th>Mean Value</th>
<th>Standard Deviation</th>
<th>Median</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>17,934.2</td>
<td>2953.6</td>
<td>17,487.0</td>
<td>11,368.0</td>
<td>24,005.0</td>
<td>0.023</td>
</tr>
<tr>
<td>II</td>
<td>31,881.4</td>
<td>8243.1</td>
<td>31,927.0</td>
<td>12,245.0</td>
<td>59,617.0</td>
<td>0.322</td>
</tr>
<tr>
<td>III</td>
<td>31,927.6</td>
<td>5511.5</td>
<td>32,837.0</td>
<td>17,555.0</td>
<td>42,533.0</td>
<td>-0.736</td>
</tr>
</tbody>
</table>

Analysis of Figure 10 and Table 6 indicates that the total thrust exerted by the shield in strata II and III is greater than that in stratum I. It is crucial to rigorously control the tunneling thrust during shield excavation to prevent tool damage and segment rupture.
In stratum II tunneling, the total thrust experiences significant fluctuations, displaying an overall increasing trend with an amplitude as high as 19,125 kN. The excavation parameters in this stratum fluctuate considerably, necessitating real-time monitoring and prompt adjustments. During excavation in stratum III, the shield’s total thrust mainly falls within the range of 30,268 to 37,780 kN. Compared to stratum II, the amplitude is smaller, making it easier to control during the excavation process. Stratum I, characterized by a soil layer of “volcanic ash debris + round gravel”, facilitates with smoother advancement. In stratum II, where the soil layer is “clay + volcanic ash debris”, the soil has substantial cementation and higher propulsion resistance. Stratum III features a soil layer of “clay + volcanic ash debris + round gravel”, exhibiting good particle gradation, minimal propulsion resistance, and a downward trend in the total thrust.

![Figure 10](image_url)  
*Figure 10. The curve of the total thrust changing with the ring number.*

In contrast to other strata [32,33], the volcanic ash strata exhibits smaller particle density, larger interparticle gaps, and higher friction resistance during shield tunneling. Consequently, at the same excavation speed, the shield in the volcanic ash strata requires a relatively larger total thrust.

### 3.6. Cutter Torque

The correlation between the cutter torque and the shield tunnel ring number is illustrated in Figure 11. Table 7 presents the statistical characteristics of the cutter torque across three distinct stratum conditions.

<table>
<thead>
<tr>
<th>Stratum Serial Number</th>
<th>Mean Value</th>
<th>Standard Deviation</th>
<th>Median</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>5287.8</td>
<td>584.3</td>
<td>5418.0</td>
<td>3897.9</td>
<td>6318.0</td>
<td>-0.544</td>
</tr>
<tr>
<td>II</td>
<td>5831.5</td>
<td>1555.0</td>
<td>5876.2</td>
<td>2769.7</td>
<td>9378.4</td>
<td>0.089</td>
</tr>
<tr>
<td>III</td>
<td>4736.7</td>
<td>1218.5</td>
<td>4482.5</td>
<td>2602.3</td>
<td>8786.1</td>
<td>0.974</td>
</tr>
</tbody>
</table>

From the analysis of Figure 11 and Table 7, it is observed that in stratum I, shield tunneling exhibits relative stability, with the cutter torque controlled at approximately 5287.8 kN·m. In stratum II, cutter resistance increases, leading to significant fluctuations and an overall increase in the cutter torque. At the strata II and III junction, the cutter resistance diminishes, resulting in a reduction in the cutter torque to 2960.6 kN·m. In stratum III, the cutter resistance progressively increases, and the corresponding torque of the cutter rises. However, the tunneling process is smoother than in stratum II. When the
shield is propelled with high torque in the stratum, the cutter wear is minimal, ensuring safe and rapid tunneling.

![Cutter Torque vs. Ring Numbers](image1)

**Figure 11.** The curve of the cutter torque changing with the ring number.

In contrast to other strata [34,35], the torque of the shield cutter head in volcanic ash formations is notably higher. This is attributed to several factors. (1) Volcanic ash strata typically possess high compressibility and viscosity. The shield cutter must overcome substantial formation resistance during excavation, necessitating an increase in the cutter torque to overcome this resistance. (2) High hardness of rock debris: volcanic ash strata contain rock debris and particles with high hardness, leading to significant wear on the shield cutter. To ensure both tunneling efficiency and tool durability, the torque of the shield cutter must be sufficiently large to provide ample cutting force during excavation. (3) Fluidity of volcanic ash strata: volcanic ash strata exhibit a degree of fluidity, causing particles to easily accumulate on the shield cutter head surface. This accumulation increases the resistance of shield tunneling, requiring an increase in cutter torque to overcome this resistance.

### 3.7. Cutter Speed

The correlation between the cutter speed and the shield tunnel ring number is illustrated in Figure 12. Table 8 presents the statistical characteristics of the cutter speed across three distinct stratum conditions.

![Cutter Speed vs. Ring Numbers](image2)

**Figure 12.** The curve of the cutter speed changing with the ring number.
Table 8. Statistical characteristics of different strata with the cutter speed.

<table>
<thead>
<tr>
<th>Stratum Serial Number</th>
<th>Mean Value</th>
<th>Standard Deviation</th>
<th>Median</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.250</td>
<td>0.038</td>
<td>1.230</td>
<td>1.202</td>
<td>1.397</td>
<td>2.074</td>
</tr>
<tr>
<td>II</td>
<td>1.344</td>
<td>0.038</td>
<td>1.333</td>
<td>1.046</td>
<td>1.486</td>
<td>−0.478</td>
</tr>
<tr>
<td>III</td>
<td>1.366</td>
<td>0.071</td>
<td>1.386</td>
<td>1.121</td>
<td>1.486</td>
<td>−1.906</td>
</tr>
</tbody>
</table>

Analysis of Figure 12 and Table 8 reveals that within the same stratum, the cutter speed undergoes minimal change. The cutter speed in formations I, II, and III gradually increases. In the relatively weak stratum I of the shield, the cutter speed of the shield tunneling cutter is deliberately maintained at a low level, with an average cutter speed of about 1.23 r/min⁻¹. This is done to minimize the disturbance caused by the cutter to the stratum. In stratum II and stratum III, where the soil strength is higher, the cutter torque is reduced by increasing the cutter speed, with the average cutter speed controlled at 1.34 to 1.36 r/min⁻¹.

Contrary to the influence of the stratum on the cutter torque in shield tunneling through volcanic ash strata, the cutter speed is intentionally kept low. This is due to several reasons. (1) A lower cutter speed ensures enough torque is transmitted to the cutter, effectively overcoming stratum resistance. (2) Reducing the cutter speed is necessary to avoid an increase in tool wear. (3) Lowering the cutter speed of the cutter is beneficial in reducing the accumulation of particles on the cutter surface, thereby minimizing the tunneling resistance.

3.8. Excavation Speed

The correlation between the excavation speed and the shield tunnel ring number is illustrated in Figure 13. Table 9 presents the statistical characteristics of the excavation speed across three distinct stratum conditions.

Figure 13. The curve of the excavation speed changing with the ring number.

Table 9. Statistical characteristics of the different strata with the excavation speed.

<table>
<thead>
<tr>
<th>Stratum Serial Number</th>
<th>Mean Value</th>
<th>Standard Deviation</th>
<th>Median</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>25.922</td>
<td>3.133</td>
<td>25.128</td>
<td>20.892</td>
<td>34.333</td>
<td>0.568</td>
</tr>
<tr>
<td>II</td>
<td>26.905</td>
<td>8.054</td>
<td>26.833</td>
<td>10.871</td>
<td>43.375</td>
<td>8.054</td>
</tr>
<tr>
<td>III</td>
<td>42.682</td>
<td>12.007</td>
<td>42.740</td>
<td>8.273</td>
<td>68.784</td>
<td>−0.107</td>
</tr>
</tbody>
</table>

Analysis of Figure 13 and Table 9 reveals that the excavation speed has undergone two main stages in the entire process. (1) Growth Stage (220–589 rings): During this phase,
the shield tunneling excavation speed experienced a rapid increase from 14.57 mm/min to 64.67 mm/min. The growth rate reached 0.136 mm/min per ring. (2) Fluctuation Stage (56–219 rings, 590–730 rings): The excavation speed fluctuated between 11.17 mm/min and 37.96 mm/min during rings 56 to 219. In stratum I and stratum II, the excavation speed was controlled at approximately 25.92 mm/min and 26.91 mm/min, respectively. In stratum III, characterized by stable soil with low resistance and nearing the end of the tunnel, the shield could maintain a high tunneling excavation speed, averaging 42.68 mm/min.

In contrast to other strata [36,37], volcanic ash formations exhibit more complex geological conditions and lower stratum stability. Shield construction in such areas is susceptible to ground deformation and subsidence. To ensure construction safety and stratum stability, the excavation speed of a slurry shield in volcanic ash strata is typically slower than in other strata, aiming to minimize the stratum disturbance. Due to the fragile formation stability of volcanic ash strata, the shield tunneling excavation speed is too fast, which will produce great vibration, which will have a great influence on the stability of the strata. The adjustment of the site tunneling excavation speed is a combination of engineering experience and site data-monitoring feedback. At the same time, soil improvement, real-time monitoring and risk management are used on site to ensure construction safety.

4. Correlation Analysis of Shield Tunneling Parameters

4.1. Correlation Analysis Methods

Correlation analysis serves not only to identify whether there is a mutual influence between the research objects but also to quantify the extent of that influence. In statistics, it is a method used to study the relationships between random variables, employing the correlation coefficient as a numerical measure [38]. Typically denoted as “r”, the correlation coefficient ranges from −1 to 1. A negative value indicates a negative correlation, a positive value indicates a positive correlation, and zero suggests no correlation. The absolute value of the correlation coefficient, denoted as “|r|”, is used to assess the degree of correlation between variables. When “|r|” is within (0, 0.2], it signifies an extremely weak correlation; within (0.2, 0.4], a weak correlation; within (0.4, 0.6], a moderate correlation; within (0.6, 0.8], a strong correlation; and within (0.8, 1.0], an extremely strong correlation.

Correlation coefficient analysis employs methods such as the Spearman correlation coefficient and Pearson correlation coefficient. Pearson correlation is commonly used in statistics but comes with prerequisites: the data must be continuous, follow a normal distribution, and exhibit a linear relationship. The Spearman correlation coefficient, on the other hand, is a rank-based measure of linear correlation that does not require specific distributional assumptions, thus offering a wide range of applications. However, its statistical efficiency is lower compared to the Pearson correlation. Consequently, Pearson correlation is employed for normally distributed data, while Spearman correlation is utilized for other cases.

4.2. Data Type Determination

Given the relative consistency of driving parameters within the same ring, it is standard practice to utilize the average values of these parameters under normal conditions as representative for each ring. To enhance the reliability of the data, the box chart method is employed to filter out anomalous data points, resulting in a dataset of tunneling parameters for 555 rings. For the purpose of statistical analysis, the following parameters are selected as the foundational data based on the project’s specific circumstances and prior analogous analyses: average mud pressure, grouting pressure, grouting amount, unearthed amount, total thrust, cutter torque, cutter speed and excavation speed [39,40].

Before conducting correlation analysis on the shield tunneling parameters, it is essential to assess whether the data adhere to a normal distribution [41]. Various methods, including numerical techniques like the S-W method and K-S method, as well as graphical approaches such as histograms, P-P diagrams, and Q-Q diagrams, are commonly employed.
for this purpose. The S-W method is suitable for small sample sizes (typically less than 50), and the Q-Q diagram assesses the data distribution similarity. In alignment with the shield tunneling data, a normal test is performed using the K-S numerical method and P-P graphical method. The normality is established if the p-value from the K-S test exceeds 0.05. The results of the normal distribution test are presented in Table 10.

<table>
<thead>
<tr>
<th>Tunneling Parameters</th>
<th>Stratum I</th>
<th>Stratum II</th>
<th>Stratum III</th>
<th>Total Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mud pressure</td>
<td>0.01</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Grouting pressure</td>
<td>√ (0.2)</td>
<td>√ (0.2)</td>
<td>0.002</td>
<td>0</td>
</tr>
<tr>
<td>Grouting amount</td>
<td>√ (0.2)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Unearthed amount</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total thrust</td>
<td>√ (0.065)</td>
<td>0.013</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cutter torque</td>
<td>√ (0.2)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cutter speed</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Excavation speed</td>
<td>√ (0.144)</td>
<td>0</td>
<td>0.002</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: √—obeys a normal distribution; ()—normal test p-value.

### 4.3. Correlation Analysis and Tunneling Strategy Optimization

Based on the normal distribution test results for the shield tunneling parameters, an appropriate correlation analysis method is chosen to examine the relationship between the tunneling parameters within specific stratum sections and the overall shield interval. The correlation findings are depicted in Figure 14.

**Figure 14.** Correlation analysis results of the tunneling parameters.

The following can be analyzed from Figure 14:

1. **Slurry Pressure and Grouting Pressure**

   In the volcanic ash strata, the disparity between the grouting pressure and the slurry pressure typically falls within the range of 0.2 to 0.3 MPa, with the grouting pressure exceeding the slurry pressure by around 0.22 MPa (see Figure 7 for details). The slurry pressure demonstrates a positive correlation with the tunnel burial depth. It is advisable to
maintain the grouting pressure approximately 0.22 MPa higher than the slurry pressure. Additionally, consideration should be given to potential ground subsidence and local uplift. Monitoring the safety of upper building structures in correspondence with ground settlement and the shield tunneling position is crucial for shallow-buried shield tunnels. This allows for timely adjustments to the grouting pressure.

(2) Grouting Pressure and Grouting Amount
In the volcanic ash strata, there exists a negative correlation between the grouting pressure and the grouting amount. The prompt and effective filling of slurry plays a crucial role in maintaining the relative stability of the soil. Should any indication of a positive correlation between the grouting pressure and the grouting amount emerge, it is imperative to conduct timely inspections of the grouting equipment to ensure smooth grouting operations and the overall safety of the shield tunneling process.

(3) Total Thrust and Slurry Pressure
In the volcanic ash strata, the total thrust is strongly negatively correlated with the mud pressure (correlation coefficient is $-0.61$), indicating that as the mud pressure increases, the total thrust setting will decrease, which is obvious in the “volcanic ash debris + round gravel” composite formation (correlation coefficient is $-0.64$).

(4) Unearthed Amount and Total Thrust
In the volcanic ash strata, there is a positive correlation between the unearthed amount and the total thrust. Specifically, in the composite stratum of “clay + volcanic ash debris + round gravel”, the unearthed amount shows a moderately positive correlation with the total thrust (correlation coefficient is 0.54). This correlation is significantly stronger than that observed in “volcanic ash debris + round gravel” and “clay + volcanic ash debris”.

(5) Cutter Torque and Total Thrust
In the volcanic ash strata, there is a negative correlation between the cutter torque and the total thrust. Specifically, in the “volcanic ash debris + round gravel” composite stratum, a strong negative correlation is observed (correlation coefficient is $-0.77$). However, in the “clay + volcanic ash debris + round gravel” composite stratum, a weak positive correlation exists. The presence of clay poses a significant hindrance to shield tunneling, necessitating attention being paid to the mud cake conditions.

(6) Cutter Speed and Total Thrust
In the volcanic ash strata, there is an extremely weak correlation between the cutter torque and the total thrust. The cutter speed primarily influences the cutting efficiency of the soil. However, the total thrust is also impacted by the soil viscosity, density, hardness, and other factors. Increasing the cutter speed enlarges the contact area between the cutter and the soil, thereby enhancing the cutting force. Yet, during actual tunneling, variations in the contact area may be influenced by factors like the shield machine’s orientation and the soil heterogeneity. Hence, the relationship between the cutter speed and the total thrust may not be strictly linear.

(7) Excavation Speed and Cutter Speed
In the volcanic ash strata, there is an extremely weak negative correlation between the excavation speed and the cutter speed. Within a certain range, the excavation speed is positively correlated with the cutter speed, as a higher cutter speed enhances the tool’s cutting ability, leading to an increased excavation speed. However, in the volcanic ash strata, factors like the tool wear and formation resistance weaken this positive correlation.

5. Prediction Performance of Tunneling Excavation Speed under Various Machine-Learning Algorithms

5.1. Machine-Learning Algorithms in Tunneling
Machine learning involves the use of models to learn from data, enabling predictions or decision-making without explicit programming. Its powerful algorithms make it an effective tool for solving complex problems, processing large datasets, enhancing efficiency, and improving user experiences [42]. In predicting shield tunneling parameters, various algorithms, such as Artificial Neural Network (ANN) [43,44], Deep Neural Network
5.2. Data Processing

The shield machine’s sensors gathered 36 types of data, focusing on key parameters like the slurry pressure, grouting pressure, grouting amount, unearthed amount total thrust, cutter torque, cutter speed, and excavation speed. Real-time collection of the shield tunneling parameters was prioritized. To ensure data reliability, the mean value of each tunneling parameter within the same ring, under normal tunneling conditions, was considered as the ring representative. To enhance the data quality, the box diagram method was applied to filter out abnormal data, resulting in the selection of tunneling parameters from a total of 555 rings as variable data.

Figure 14 reveals that the linear correlation coefficient between the excavation speed and other parameters is generally small, with the maximum correlation coefficient reaching 0.46. Linear correlation analysis struggles to determine the extent of influence of the other tunneling parameters on tunneling excavation speed due to the highly nonlinear relationship within the data. Traditional linear analysis methods are inadequate in this context.

The Maximum Information Coefficient (MIC) serves as a method for detecting nonlinear correlations between variables, addressing the limitations of linear correlation measures like the Pearson correlation coefficient in handling nonlinear relationships. Calculating the MIC relies on information theory principles, quantifying the correlation degree between two variables. A higher MIC value indicates a stronger nonlinear correlation, ranging from 0 to 1. A value close to 1 signifies a robust nonlinear correlation, while proximity to 0 implies a minimal nonlinear correlation. The MIC calculation formula is presented in Formulas (1) and (2).

\[
I[X; Y] = \sum_{X,Y} p(X, Y) \log_2 \frac{p(X, Y)}{p(X)p(Y)}
\]  

(1)

\[
\text{MIC}[X; Y] = \max_{|X||Y| < N^0.6} \frac{I(X; Y)}{\log_2 \min(|X|, |Y|)}
\]  

(2)

In these formulas, \(X\) and \(Y\) are variable names, \(N\) is the number of samples, and \(p(X, Y)\) is the joint probability of variables \(X\) and \(Y\).

After data preprocessing, Python 3.6 software is employed to compute the MIC values between the excavation speed and the seven other tunneling parameters. The calculation outcomes are presented in Table 11. Given the shield tunneling context, the slurry pressure, excavation volume, grouting pressure, and cutter head torque, exhibiting MIC values surpassing 0.4, are ultimately chosen as the reference variables.

In machine-learning algorithms, data standardization (or normalization) is a widely employed preprocessing technique. Its primary purpose is to mitigate the impact of different scales between features, ensuring each feature holds equal importance. This facilitates a comprehensive analysis and comparison of indicators with varying units or magnitudes, enhancing the model accuracy and stability. Z-score standardization is utilized
for a linear transformation of the original data, mapping the results to the range \([-1, 1]\), as depicted in Formula (3).

\[ x' = \frac{x - \mu}{\sigma} \]  

(3)

In the formula, \(x'\) is a standardized value, \(x\) is the original data value, \(\mu\) is the mean value of the sample data, and \(\sigma\) is the standard deviation of the sample data.

5.3. Calculation Results

Leveraging Python software for computation, a 70% portion is designated as the training set, and the remaining 30% serves as the test set. The error values for the six machine-learning algorithms are illustrated in Figure 15.

![Comparison of the models' error values.](image)

The mean square error (MSE), root mean square error (RMSE), mean absolute error (MAE), and determination coefficient (R²) are chosen as performance evaluation metrics for the prediction models across the different algorithms. The outcomes are presented in Table 12.

Table 12. Comparison of the evaluation indexes of the models.

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>MSE</th>
<th>RMSE</th>
<th>MAE</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANN</td>
<td>46.960</td>
<td>6.853</td>
<td>4.964</td>
<td>0.691</td>
</tr>
<tr>
<td>DNN</td>
<td>41.756</td>
<td>6.461</td>
<td>4.711</td>
<td>0.725</td>
</tr>
<tr>
<td>BPNN</td>
<td>50.035</td>
<td>7.611</td>
<td>5.581</td>
<td>0.611</td>
</tr>
<tr>
<td>SVM</td>
<td>84.456</td>
<td>9.190</td>
<td>6.764</td>
<td>0.444</td>
</tr>
<tr>
<td>MNR</td>
<td>64.174</td>
<td>8.011</td>
<td>6.085</td>
<td>0.577</td>
</tr>
<tr>
<td>RF</td>
<td>25.955</td>
<td>5.094</td>
<td>3.468</td>
<td>0.829</td>
</tr>
</tbody>
</table>

Table 12 reveals that the RF model outperforms the others, displaying the lowest mean square error, root mean square error, average determination error, and the highest determination coefficient. This suggests that the RF model excels in predicting the tunneling excavation speed. Conversely, the SVM and MNR models exhibit poor performance, suggesting potential unsuitability for this prediction task. The performance of the BPNN, DNN, and ANN models is relatively close in each index but falls short of the RF model.

6. Conclusions

This study focuses on the No. 1 Tunnel project of the Jakarta–Bandung High-Speed Railway, examining the variation patterns and correlations of the tunneling parameters
during shield tunneling through volcanic ash strata. The prediction performance of six algorithms in terms of the excavation speed is compared and analyzed.

(1) In the volcanic ash strata, there is a positive correlation between the slurry pressure and the tunnel depth. The recommended grouting pressure is approximately 0.22 MPa higher than the slurry pressure. The total thrust shows a strong negative correlation with the mud pressure, reaching $-0.77$ in the "volcanic ash debris + round gravel" composite strata. The cutter speed exhibits weak or extremely weak correlations with the total thrust, and the tunneling excavation speed is extremely weakly negatively correlated with the cutter speed.

The data are derived from the correlation analysis of the shield tunneling parameters in Section 4, as shown in Figure 13.

(2) In contrast to other strata, the volcanic ash strata exhibits high cementation, compressibility, and heterogeneity. During shield tunneling, the grouting pressure experiences considerable fluctuations. The shield tunneling excavation speed is deliberately slower in volcanic ash strata to minimize strata disturbance. Under the same propulsion speed, the volcanic ash strata demands a higher total thrust for the shield, resulting in significantly larger cutter head torque and a lower cutter speed.

(3) In the context of predicting the shield excavation speed, the RF model outperforms the others, exhibiting the lowest MSE, RMSE, and MAE. The $R^2$ reaches 0.829, indicating superior predictive accuracy. Conversely, the SVM and MNR models demonstrate poor performance, suggesting limited suitability for excavation speed prediction.

Author Contributions: Conceptualization, Z.T. and J.Z.; methodology, X.F.; software, X.F.; validation, X.F., J.Z. and B.Z.; formal analysis, X.F.; investigation, X.F., Y.C. and Y.J.; data curation, B.Z.; writing—original draft preparation, X.F.; writing—review and editing, X.F., J.Z. and B.Z.; visualization, Z.T. and X.F.; project administration, Y.C. and Y.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in [reference].

Conflicts of Interest: Authors Yuxin Cao and Yongtao Jiang were employed by the company Power China Railway Construction Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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