Experimental study and field validation on soil clogging of EPB shields in completely decomposed granite

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\textbf{ABSTRACT}

Clogging may occur inside the shield machine during earth pressure balance (EPB) tunnelling in cohesive soils. Soil conditioning can be used to reduce clogging potential and ensure the efficiency of the shield tunnelling. The current methods used to assess the clogging potential mainly focus on pure clayey soils or artificial mixed soils, the clogging in natural weathered soils is less studied. This paper studied the clogging when tunnelling in completely decomposed granite by laboratory tests, followed by field validation. In the laboratory tests, the torque and excavation speed were recorded and the soil distribution on the cutting device were analyzed. It appeared that when clogging happens, the excavation speed drops and the fluctuation in speed increases, while the torque rises as well as the fluctuations in the torque. Clogging first covers the cutters, then fill in the intervals between cutters, and finally blocked the openings on the cutting device. The opening at the central part of cutting device is of vital importance to prevent clogging. The process of clogging can be divided into three stages, the initial stage, the stabilized stage and the clogging stage. In-situ data from Guangzhou Metro Line 21 showed that clogging on cutterhead was effectively avoided when using the recommended soil conditioning scheme. Furthermore, the clogging evaluation method and process of clogging proposed are consistent with field validation and with current major clogging assessment method.

1. Introduction

EPB shields are widely used as safe and efficient tunnelling machines. When tunnelling in cohesive soils, soil may stick to the shield machine and cause clogging. Clogging will reduce the penetration of cutters, resulting in the excessive wear of cutters and a low efficiency tunnelling. By injecting water, foam or anti-clay polymer into soils, the clogging potential can be controlled.

Although clogging potential of cohesive soils has been previously studied by many scholars, which leads to abundant valuable achievements, the studies about clogging in natural weathered soils are limited. The knowledge about the comparison between clogging potential laboratory tests with on-site validation is also not extensive. Besides, serious clogging may show up in low clogging potential soils due to the neglect of clogging potential, the high thrust applied and the lack of soil conditioning. It is important to monitor and distinguish when clogging may show up during tunnelling.

This paper tested in-situ soils of an EPB tunnelling project in Guangzhou, China. In this project, serious clogging occurred when tunnelling in completely weathered granite. The completely weathered granite in this project has a relatively low clay content. Regular foam is therefore selected instead of foam with anti-clay polymer or dispersant to study this unexpected clogging.

The purpose of this paper is to study the relationship between tunnelling parameter changes and clogging, to study the clogging distribution at the cutting device and to compare laboratory data with field work. A laboratory device which can simulate shield tunnelling to a certain extent was built and used to meet this purpose. The torque and excavation speed during the laboratory tests were recorded and analysed. The soil distribution on the cutting device was analysed and the process of clogging is described. Finally, the field validation was performed at Guangzhou Metro Line 21.
2. Background

Clogging potential can be reduced by injecting foam as anti-clogging agent at the cutterhead, the pressure chamber and the screw conveyor during tunnelling in clay (Thewes, 1999; Langmaack, 2000; Langmaack and Lee, 2016). With successful soil conditioning, the conditioned soil will have a relatively low cohesion and shear strength, a proper compressibility and workability and a suitable consistency index (EFNARC, 2005; Milligan, 2000; Thewes and Budach, 2010). Concentration of foaming agent ($C_f$), foam injection ratio (FIR) and foam expansion ratio (FER) are key parameters concerning soil conditioning, which can be defined as follows:

$$C_f = \frac{m_{sur}}{m_f} \times 100$$  \hspace{1cm} (1)

where $m_{sur}$ is the mass of surfactant, in this paper, the mass of foaming agent and $m_f$ is the mass of foaming solution.

$$FIR = \frac{V_f}{V_s} \times 100$$  \hspace{1cm} (2)

where $V_f$ is volume of foam and $V_s$ is the volume of soil to be treated.

$$FER = \frac{V_f}{V_{foam}}$$  \hspace{1cm} (3)

where $V_f$ is the volume of foam and $V_{foam}$ is the volume of foaming solution.

The workability is widely studied by slump tests to ensure the effect of soil conditioning (Peila et al., 2013; Peila et al., 2016; Peila et al., 2019). Yet in cohesive soil, slump test is not feasible as the soil is usually in a plastic state (Oliveira, 2018; Oliveira et al., 2019), the consistency index $I_c$ is used instead. The consistency index is defined as follows:

$$I_c = \frac{w_s - w_p}{w_l - w_p}$$  \hspace{1cm} (4)

where $w_s$ is the liquid limit, $w_p$ is the plastic limit and $w_l$ is the natural water content of clay.

Hollmann and Thewes (2012, 2013) proposed the universal clogging potential diagram based on the consistency index and tunnel data, as shown in Fig. 1.

The feasibility of this diagram has been proven through pull-out tests (Khabbazi et al., 2019; Barzegari et al., 2020), plate shear tests (Wang et al., 2020), Hobart mixing tests (Oliveira, 2018; Oliveira et al., 2018; Oliveira et al., 2019) and model tests (Milatz et al., 2019).

Pull-out tests provide a method to study clogging by measuring the adhesion between metal and soils. Thewes and Burger (2005) studied clogging through pull-out tests and found that the two main factors to the adhesion between soil and steel are the content of clay minerals and the consistency index. Sass and Burbam (2009) found that the adhesion between soil and a metal cylinder in pull-out tests remained relatively constant despite the change of the metal of the cylinder used, which shows the importance of soil conditioning on the reduction of clogging potential. Khabbazi et al. (2019) checked the accuracy of current clogging potential diagram by over three hundred groups of pull-out tests. Wang et al. (2020) found that dispersant can reduce the tangential adhesion stress between soil and metal.

Hobart mixing tests provide an easy qualitative way to assess soil clogging. As the test device of the Hobart mixing tests is relatively simple, the clogging potential assessment method based on this has the potential to be standardised. Zumsteg and Puzrin (2012) used the ratio between the mass of soil stuck to the Hobart mixing tool and the weight of all soil samples in the mixer to study the clogging issue. Oliveira et al. (2019) brought up the ATUR (Adhäsive Tone Untersuchung RUB-Queen) device which enables the free fall of the mixing tool of Hobart mixing tests from the height of 37 cm. By performing extensive Hobart-ATUR tests with cohesive soils, the authors brought up a clogging potential assessment method based on the clogging parameter $\lambda_F$.

The clogging potential is high with $\lambda_F$ higher than 0.48 while the clogging potential is low with $\lambda_F$ lower than 0.27. The clogging parameter $\lambda_F$ can be defined as follows:

$$\lambda_F = \frac{G_M}{G_{TOT}}$$  \hspace{1cm} (4)

$$\lambda_F = \frac{\lambda_b + \lambda_1 + \lambda_2 + \lambda_3 + \lambda_7}{5}$$  \hspace{1cm} (5)

$$\lambda_F = \frac{\lambda_F}{CB_{Factor}}$$  \hspace{1cm} (6)

where $G_{TOT}$ is the mass of soil stuck at the mixer after x (x being 0, 1, 2, 3, 7) times of free fall, $G_{TOT}$ is the total mass of the soil, $\lambda_F$ is the average value of the recorded $\lambda_F$ values, $\lambda_F$ is the clogging parameter. $CB_{Factor}$ is the cleaning beater and bowl factor, with the value between 0.5 and 3.0. Reading the original paper Oliveira et al. (2019) is strongly recommended, when the readers want to use the clogging parameter $\lambda_F$, as the determination of $CB_{Factor}$ is explained there in detail with words and figures.

Model tests are another way to study the influence of soil conditioning, yet most of the studies focused on the workability or the flowability of conditioned soil (Bezuijen et al., 1999; Bezuijen and Schaminee, 2000; Bezuijen and Schaminee, 2001; Merritt and Mair, 2006; Peila et al., 2007; Vinai et al., 2008), model tests focusing on clogging are less described in literature. Milatz et al. (2019) studied clogging and tool abrasion by model tests. They found that the bentonite suspension placed at the cutterhead at the beginning of the tests will increase the soil mass stuck at the cutterhead and decrease the tool abrasion. Feinendegen et al., (2011) recorded increasing torque and thrust when clogging occurred during model tests.

Clogging has also been studied by in-situ tunnelling data analysis (Jancsecz et al., 1999; Feinendegen et al., 2012; Mosavat and Mooney, 2015; Avunduk and Copur, 2019), it has been found that clogging usually leads to a decrease of excavation speed, the increase of torque and consequently to an increase of the energy needed for tunnelling.

3. Material and methods

3.1. Tested material

The completely decomposed granite collected from Guangzhou Metro Line 21 was used in the laboratory tests. The soil was collected from an air shaft at the same depth as the shield machine. In order to...
preserve the natural moisture content, the soil was stored in sealed plastic bags during transportation. The natural water content, plastic limit and liquid limit were then tested for 5 times in the laboratory, the average values are 19.8%, 14.5% and 28.9% and the standard deviations are 0.71%, 0.85% and 1.45%, respectively. The completely decomposed granite was then oven dried and sieved to remove particles with diameters larger than 10 mm. As the minimum width of most openings on the cutting device in the laboratory tests is 30 mm, soil will not be clogged due to the restriction of opening size. After removing large particles, the grain size distribution of the tested soil sample can be shown in Fig. 2.

The mineral composition of the soil sample is shown in Table 1. Table 1 and Fig. 2 shows that the soil is in the CL (clay low) class and within the low plasticity, thus regular foam was chosen as conditioner instead of dispersant or foam with anti-clay polymers. Three products were chosen as alternative products and their surface tensions were tested by the Wilhelmy plate method at the temperature of 25 °C, as shown in Fig. 3. The names of the foaming agents were replaced with code names to avoid any advertisement. It can be seen that all foaming agents reached the lowest surface tension between the concentration of 3% to 4%.

The general descriptions and the half-life times of the three products are shown in Table 2. The half-life time was tested by a filtered funnel with diameter of 13 cm according to EFNARC (2005) and Wu et al. (2018). The FER of the tested foam was 10 and the C_f was 3.5%. Since product A had the longest half time this product was chosen by the contractor in the field and was therefore also used in the laboratory tests.

The foam was generated by the setup in Fig. 4. The generator is a small-scale reproduction of an original foam generator in an EPB shield, filled with glass balls with the diameter of 5 mm. A similar generator was used by other scholars (Galli, 2016; Oliveira et al., 2019; Hu et al., 2020). The flow of foaming agent and compressed air was controlled by flowmeters. The flowmeters were built with accuracy to gain foam with stable FER. The C_f in all subsequent tests was chosen as 3.5% and the FER was chosen as 10 at atmospheric pressure. By measuring the generated foam in a container with known volume and weight, it has been found the FER of foam generated is between 9.7 and 10.2, near the target FER 10.

### 3.2. Proposed methodology

In the proposed methodology, three groups of tests were performed, each group of tests were performed with soil samples conditioned with FIR from 0% to 120% at an interval of 20%. The soil samples of the latter two groups must be recycled as the amount of the in-situ soil in the laboratory was limited. The field validation was performed after the laboratory tests. Fig. 5 shows the flow table of this methodology.

The soil samples were first collected and sealed at the job site, then shipped to the laboratory. The natural water content and Atterberg limits were then tested in the laboratory. The soils were oven dried and broken into particles to remove particles with diameters larger than 10 mm and to test the grain size distribution.

For soils first tested (Group 1), the dried soils were carefully mixed to make sure soil particles were homogeneously distributed. Water was then added to reach the target water content 19.8%. The wet soils were mixed for 10 min and sealed for 24 h to get soil sample with desired water content. The water content and Atterberg limits of the soil sample were then measured before proceeding to test stage.

For soils recycled, the additives in Group 1 should be removed as much as possible. The soils were first dried and broken into particles to enlarge the superficial area of the whole soil sample. The dried soil particles were then immersed in water for 12 h. The water above was carefully removed before the soil samples were oven dried and broken into particles again. The procedures were repeated again before the grain size was tested. The next steps in the soil preparation procedure are the same with soils first tested, as shown in Fig. 5. The grain size distribution in Fig. 2 shows that almost no fine particles were lost when recycling the soil samples. The Atterberg limits were measured by the fall cone test according to National Standard of the People’s Republic of China.
China (2019). The water content and Atterberg limits of the reconstituted soil samples are shown in Table 3. It shows that the soil preparation stage can provide controllable reconstituted soil sample and the Atterberg limits of the soil sample is near that of in-situ soils.

The setup used for the test stage is shown in Fig. 6. The aim of the setup was not to make a real scale model test of a TBM, but to acquire comparable conditions as in a TBM, to be able to compare the behaviour of soil and different foam conditions. A hydraulic jack was installed to a steel plate to apply pressure on the soil in the soil chamber which has a diameter of 310 mm. The soil chamber can be filled through an opening at the top. A cutting device with a diameter of 300 mm and a thickness of 20 mm was installed on a motor to simulate shield tunnelling. A steel soil cover can be installed over the openings of the cutting device when filling soil to make a better soil sample. A torque sensor was installed between the cutting device and the motor to record the torque during test. The speed of the pressure plate and the soil distribution on the cutting device after excavation can also be recorded.

When performing tests with this setup, the steel soil cover was first installed. The soil and foam were mixed at 1 bar by a mixer for 3 min to ensure the uniformity of the mixture. The conditioned soil was then filled in a loose state in the soil chamber through the opening at the top. The conditioned soil was filled in five layers, each layer was carefully made even to reach a high and constant density after being pressurized. The pressure of 3 bar was then applied on the soil through the pressure plate and held constant throughout the tests. After removing the steel soil covers from the cutting device, the motor was started with a constant rotation speed of 1.5 rpm, which is the same rotation speed in the following field validation section. The torque and excavation speed were measured with a frequency of 0.1 Hz. After the tests, the cutting device was removed, photographed and weighted to calculate the total soil stuck (Gt). In test Group 1, the soil stuck in different areas (Gλa) was weighted by removing soil stuck to the cutting device with scraper. The areas were divided as shown in Fig. 7. In test Group 2 and 3, the free fall of cutting device was performed, at direction A and direction B from the height of 80 cm with a wooden base. The free fall at each direction was repeated for 7 times. The free fall was performed at two directions as the cutters at horizontal direction will prevent the soil above from falling. Afterwards, the cutting device was photographed and weighted to calculate and total soil stuck after free fall (Gdf). The soil stuck in different areas after free fall (Gdf) was then weighted by removing soil stuck with scraper. The ratios of soil stuck (λa, λdf) before and after the free fall can then be calculated.

\[ \lambda_a = \frac{G_{df}}{G_a} \]  
\[ \lambda_{df} = \frac{G_{df}}{G_{a}} \]  

Finally, the proposed soil conditioning scheme was adopted in actual tunnelling, the tunnelling parameters were analyzed.

3.3. Foam loss test

In actual tunnelling, soil and foam were mixed under pressure. Yet in the laboratory tests, the soil and foam were mixed at 1 bar and the mixture was pressurized. Foam loss tests were performed to verify the foam decrease and possible collapse under pressure. Immersed saturated soil was used for the foam loss tests, as the void inside the soil sample should be filled with water to ensure air only exists inside the foam. The saturated soil tested in the foam loss tests was not used in the main methodology, making the foam loss test independent of the main methodology.

The foam loss tests were performed by a permeameter following ASTM D2434-68. Air pressure can be applied through the valve on the top cover while drainage can be controlled by the valve on the bottom cover. The oven dried soil particles were first submerged with water for 48 h to ensure a fully saturated status. The fully saturated soil was then mixed by mixer with foam carefully for 3 min to ensure the homogeneity of the conditioned soil. It is regarded no bubble collapsed during the mixing. The conditioned soil was then placed in the acrylic cylinder for 4 layers, the height of each layer was 5 cm. Special attention was paid to ensure the close contact between each layer. As the soil was fully saturated before conditioning and special attention was paid to ensure no interspace exists when preparing the soil sample, it is regarded that no air exists except for the volume of air in the foam. Considering the volume of foam (Vf) equals to the volume of air plus the volume of solution, the volume of air at 1 bar (Vg) can then be calculated based on Eq. (2) and Eq. (3) as follows:

\[ V_g = V_f - \frac{V_f}{FER} \]  

Air pressure of 3 bar was then applied on top of the soil sample. The
valve on the bottom cover remained sealed throughout the foam loss tests. The volume decrease of air ($\Delta V_a$) under pressure can be obtained by measuring the height decrease of the soil sample, as the volume of water and soil remains constant. With the measured volume decrease of air, the volume of air under the air pressure of 3 bar ($V_a'$) can then be calculated as follows.

$$V_a' = V_a - \Delta V_a$$  \hspace{1cm} (10)

According to Boyle’s law, the theoretical ratio between the volume of air under the air pressure of 3 bar plus atmospheric pressure ($V_a'$) and the volume of air under atmospheric pressure ($V_a$) should be 1/4. The calculated ratios were between 0.97/4 to 0.99/4, it is then concluded that hardly any bubbles collapsed when pressurizing the conditioned soil.

4. Test results

4.1. Excavation speed with various FIRs

Fig. 8 shows the time-history curves of excavation speed. The curves of each group are shown independently, as the average values may cause reduction to the fluctuations in the time-history curves and thus influence the judgement of the test results. As shown in Fig. 8, the initial excavation speed, with the constant pressure of 3 bar and the constant rotation speed of 1.5 rpm, was faster in the tests with larger FIR. In all tests, the excavation speed experienced a rapid decrease at the initial stage. After that, the decrease slowed down and finally reached a relatively stable stage with some fluctuations. Besides, when FIR is higher than 80%, the fluctuations of the excavation speed at the end of the test were greatly reduced, indicating that the soil has a lower viscosity at higher FIR.

It can be seen that the test can be divided into three stages. In Stage I the excavation speed had a sharp decrease, this is because the soil

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Table 3
Water contents and Atterberg limits of reconstituted soil samples.

<table>
<thead>
<tr>
<th>Property</th>
<th>Average value</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content $w_1$ (%)</td>
<td>19.71</td>
<td>0.28</td>
</tr>
<tr>
<td>Plastic limit $w_p$ (%)</td>
<td>14.61</td>
<td>0.54</td>
</tr>
<tr>
<td>Liquid limit $w_l$ (%)</td>
<td>28.41</td>
<td>0.68</td>
</tr>
<tr>
<td>Consistency index $I_c$</td>
<td>0.63</td>
<td>0.04</td>
</tr>
</tbody>
</table>

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Fig. 5. Flow table of proposed methodology.
inevitably stuck to the cutting device during the tunnelling in clay, which reduced the efficiency of cutters and then reduced the excavation speed. In Stage II the excavation speed was relatively stable and decreased slowly because the soil started to stick at the interval between cutters, and then reduced the penetration of cutters. When FIR is less than 60%, there is also a Stage III. In Stage III, the standard deviation of excavation speed increases.

The durations and deviations of the three stages of clogging in different tests is shown in Fig. 9. In Stage I, the excavation speed decreased greatly, the point at which excavation speed increased first is taken as the critical point between Stage I and Stage II, as shown in Fig. 8. The critical point between Stage II and Stage III is the point where excavation speed starts to fluctuate significantly. As FIR increases, the duration of Stage I and Stage II increases, and the duration of Stage III decreases at the same time. When FIR reaches 80%, Stage III no longer exist during the test, indicating that the tunnelling process was stable, and clogging was avoided. The deviations of the clogging stages increased significantly when FIR reaches 100%, also indicating that the excavation was quite steady, thus the boundaries between stages became less clear.

The standard deviations of excavation speed in Stage II and Stage III are shown in Fig. 10. It can be seen that the standard deviation dropped with the increase of FIR, and the standard deviations of Stage III are higher. The standard deviations of the three performed groups also dropped with the increase of FIR. The average values of excavation speed in Fig. 10 show that the increasing FIR increased the excavation speed.

According to the analysis above, Stage II can be regarded as the optimal state for shield tunnelling in clay, with only small amount of soil stuck to the cutter. Keeping the tunnelling process in this stage can avoid soil from filling the interval between cutters and blocking the openings. In order to facilitate the comparison of the test data with various FIRs, test data was processed using the speed percentage \( k_v \).

\[
k_v = \frac{\nu}{\nu_a}
\]  

(11)

where \( \nu_a \) is the average speed of Stage II and \( \nu \) is the speed during the whole test.

Fig. 11 shows the time history curves of speed percentage. Take Group 1 as example, in Stage I, for test groups with FIRs less than 80%,

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Fig. 6. Setup for soil clogging test: bottom right plots the steel soil cover.

Fig. 7. Different areas of the cutting device.
the speed dropped sharply, showing that soil stuck to cutters quickly due to the high cohesion. In Stage II, the speed of test group with FIR 0% started to fluctuate, indicating that the opening on cutting device may had already been clogged. In Stage III, for test groups with FIRs less than 80%, the fluctuation became bigger with the decrease of FIR. For test groups with FIRs more than 80%, the Stage III was not reached because the speed kept stable until the end of the test. Thus, the minimum speed percentage in test with FIR 60% was taken as the critical point between low and medium clogging potential, that is, $k_v = 85\%$. The minimum speed percentage in test with FIR 40% was taken as the critical point between medium and high potential, that is, $k_v = 60\%$. It can be seen that the results of Group 2 and Group 3 both fit the clogging potential.

4.2. Excavation torque with various FIRs

As shown in Fig. 12, the initial torque was smaller with larger FIR. For all cases, the torque experienced a rapid increase at the initial stage. After that, the increase slowed down and reached a relatively stable stage with some fluctuations. For soil with FIR 0%, 20%, 40%, the torque increased again with great fluctuation. Like the excavation speed
analysed in the previous section, when FIR is higher than 80%, the fluctuation of the torque during the test was significantly reduced. There’s also a huge soil conditioning performance improvement in torque value at FIR 80%.

The clogging process divided by the torque is shown in Fig. 13, and the stages are divided in the same way as in the previous section. Fig. 13
shows that, for Stage I and Stage II, the duration generally increased with the increase of FIR.

The standard deviations and average values of torque in Stage II and Stage III (Fig. 14) have the similar trend as Fig. 10.

Like the section above, take Stage II as the optimal state for shield tunnelling, test data was processed using the torque percentage $k_T$.

$$k_T = \frac{T}{T_a}$$  \hspace{1cm} (12)

where $T_a$ is the average torque of Stage II and $T$ is the torque during the whole test.

Fig. 15 shows the trends of torque percentage in Stage II and Stage III are similar to those of speed percentage, as FIR increased, the fluctuation decreased. Take Group 1 as example, the maximum speed percentage in the test with FIR 60% is taken as the critical point between low and medium clogging potential, that is, $T_v = 107.5\%$. The maximum speed percentage in test with FIR 40% is taken as the critical point between medium and high potential, that is, $k_T = 112.5\%$. It can be seen that the
Fig. 14. Standard deviations and average values of torque in Stage II and Stage III.

Fig. 15. Time history curves of torque percentage.
results of Group 2 and Group 3 both fit the clogging potential.

4.3. Clogging at the cutting device

The cutting device used in the tests described in this paper has a thickness of 20 mm, is 300 mm in diameter and is equipped with 1 central cutter, 32 scrapers and 12 hobs. The opening ratio of the cutting device is 36.5%.

The cutting device and soil distribution before free fall is shown in Fig. 16. In the center of the cutting device, soil is supposed to be discharged fluently through the opening due to the minimum torque. However, Fig. 16 shows that when FIR is lower than 40%, the central cutters were almost covered by soil, indicating clogging might be serious. In practice, these central cutters are used to break soil or rocks. With soil covered, these cutters may fail to cut soil loose. Thus, more force will be applied on other cutters, which will make clogging on other cutters more serious. When FIR is higher than 60%, the central cutters was no longer covered with soil indicating that the potential of clogging was reduced. For groups with FIR higher than 80%, except for the central cutters, the entire cutting device was covered with mud-like soil. This shows that when the central openings are large enough, the soil in front of the cutting device can be quickly removed, and the clogging potential can be reduced.

However, not all soil stuck shown in Fig. 16 can be regarded as clogging, as some of them may be removed with ease. By removing some soils with free fall dropping (see section 3.2), the soil distribution in Fig. 17 can show the clogging situation better, because this shows the soil really stuck to the cutter. At FIR 0%, the central cutters were still covered with soil and the central openings were filled with soil. Extensive soil covers the edge cutters, yet most soils stuck at edge openings were removed. When FIR is between 20% and 60%, the soils at central cutters and central openings were partly removed, fewer soil covered the edge cutters. For groups with FIR higher than 80%, most soils at central cutters, central openings, edge soils and edge openings were removed by the free fall. The whole cutting device was covered with a layer of soil that can be easily removed by hand. The soil stuck at the central part was the hardest to be removed by free fall. It can be seen that clogging is most likely to occur at the central part of the cutting device and the clogging here is most serious. Thus, the central opening is of vital importance, it could be designed big if the stability of the tunnel face can be ensured.

With a big central opening, the soils at the central part of the cutting device can be removed smoothly and then the clogging potential can be reduced.

The total soil stuck ($G_t$) and the soil stuck in different areas ($G_a$) before free fall are analysed, together with the total soil stuck ($G_{af}$) and the soil stuck in different areas ($G_{af2}$) after the free fall. The $G_{af}$ of the three test groups at FIR 0% are 1496 g, 1589 g and 1540 g, respectively. It shows that the value $G_t$ has a certain repeatability between groups, the laboratory tests can be regarded as repeatable to some extent on the aspect of soil stuck weight. Thus, the $G_{af}$ values which were only tested in Group 1 can be used in Group 2 and Group 3. However, the analysis of soil stuck weight is more valuable as a qualitative analysis. The value $G_t$ has a certain randomness as the shape of the cutting device is complex. This randomness is mainly caused when removing the cutting device. The value $G_{af}$ also has randomness as it is directly related to $G_t$. The values $G_a$ and $G_{af}$ also have a certain randomness as it is hard to distinguish and separate the soil stuck at the boundary between different areas.

Thus, the weight of soil stuck is analysed as the average value between Group 2 and Group 3, as shown in Fig. 18. The values $G_{af}$ to $G_{af5}$ are the soil stuck weight at different areas of the cutting device, as shown in Fig. 7. Fig. 18 shows that most of the soil stuck values decreased with increasing FIR, a major decrease can be found between FIR 40% and 80%. The soil stuck values remained relatively constant when FIR is higher than 80%. The values of $G_{af}$ and $G_{af5}$ show the amount of soil at steel board increased between FIR 40% and 80% and remained constant afterwards. Yet the soils can be removed with ease.

Fig. 19 shows the ratios between the weight of soil stuck before and after free fall. The ratios are defined in Eq. (7) and Eq. (8). The values $\lambda_1$, $\lambda_{af1}$ and $\lambda_{af2}$ decreased with increasing FIR, indicating high FIRs make the removal of stuck soil easier. The value $\lambda_{af5}$ increased significantly between FIR 0% and FIR 60%, as soils removed from other areas may stuck at the steel board. The values $\lambda_{af}$ and $\lambda_{af5}$ remained constant or increased with increasing FIR, as soil conditioning reduced the amount of soil stuck at the cutters before free fall.

To help understand the difference between soil distribution with FIR 60% and soil distribution with FIR 80%, Fig. 20 shows the difference of discharged soil. Fig. 20 is taken from two independent tests, only the picture of discharged soil is analyzed, other data is not. During other tests, the discharged soil was cut off by a sharp knife carefully once it’s
near the plate at the back of the cutting device, trying to minimize the
disturbance to the soil on and ahead of the cutting device. Thus, the
plate at the back of the cutting device won’t block the soil movement at
the center of the wheel.

For FIR 60%, the discharged soil was squeezed through the cutting
device due to the insufficient workability. For FIR 80%, although the
cutting device was covered with soil, soil on and ahead of cutting device
can be discharged through the opening easily due to the low cohesion
and sufficient workability.

From the analysis above, FIR is of vital importance for clogging. If
FIR is too low, the clogging could be a serious problem. If FIR is too high,
isufficient pressure in pressure chamber and excess surface settlement
may occur. For the test materials used in this paper, the best FIR for the
precaution of clogging is 80%.

5. Validation of findings

5.1. Engineering background

Jinkeng-Zhenlongnan section of Guangzhou Metro Line 21 in China
was conducted by an EPB machine. Buildings in this section are dense, as
shown in Fig. 21. The buildings in this section are old and are mainly
built on shallow foundations, which makes them extremely sensitive to
surface settlement.

The EPB shield in this project has a diameter of 6.0 m and an opening
ratio of 35%. The buried depth of shield tunnel is 12 ~ 22 m and the
average water level is 3.78 m. The tunnel mainly crosses strong
weathered granite, completely decomposed granite and sandy clay. The
completely decomposed granite studied in this paper was taken from the
No.2 air shaft, as shown at the very right of Fig. 22.

The contractor neglected the possibility of clogging in this section.
The soil conditioning scheme in completely decomposed granite

Fig. 17. The cutting device and soil distribution after free fall.

Fig. 18. The weight of soil stuck before and after free fall.

Fig. 19. The ratio between the weight of soil stuck before and after free fall.
remains unchanged with that in medium and strong decomposed granite. Besides, the shield driver increased the thrust when the excavation speed decreased due to clogging. The increased thrust made clogging worse. Thus, clogging was serious at the early stage of the tunneling process, as shown in Fig. 23. The serious clogging greatly reduced the efficiency of the cutterhead and the excavation speed, extended the tunneling time, and caused excess surface settlement. The old buildings with shallow foundations are therefore under great threat. Thus, avoiding clogging was a top priority for this project.

5.2. Field validation

Before Ring 528, the importance of soil conditioning was not fully understood, the soil conditioning scheme was developed using experience of similar projects, few tests were carried out. From ring 529, the new soil conditioning scheme recommended following the results described in the previous sections of this paper (the concentration of foaming agent is 3.5%, the FER is 10 and the FIR is increased from 40% to 80%) was adopted. Since the geological conditions in Ring 460–528 and Ring 529–760 are similar and the rotation speed was around 1.5 rpm in both sections, the torque, thrust and tunneling speed in the two sections are compared, as shown in Fig. 24 and Table 4.

Fig. 24 (a) and Table 4 show that the average excavation speed with Scheme 1 is 81.9% of the excavation speed reached in Scheme 2. Using the speed percentage $k_v$ mentioned above as the standard, the tunneling process was in a medium clogging potential with Scheme 1. However, this is because the excavation speed in Scheme 2 was limited. As shown in Fig. 21 and Fig. 22, in the section with Scheme 2, the shield tunnel under crosses many old shallow foundation buildings. Thus, the excavation speed was limited to meet a stricter surface settlement requirement. The quality of synchronous grouting can also be better ensured with a limited excavation speed. Thus, the position of shield machine and the direction of tunneling can be controlled with accuracy. With an almost constant rotation speed around 1.5 rpm, Fig. 24 (a) also indicates that less soil covers the cutters, thus there is limited clogging. For sections without old buildings on the ground, the excavation speed can be higher with the same rotation speed of 1.5 rpm by reducing the pressure in the excavation chamber because the surface settlement requirement is
Fig. 24 (b) and Table 4 show that after adopting the soil conditioning Scheme 2, the average thrust dropped 10.26%, from 14.13MN to 12.68MN. One of the reasons for the reduction of thrust is, the shield driver may have reduced the thrust on purpose to minimize the influence of shield tunneling on surrounding soil. But Fig. 24 (a) shows that with a lower thrust, the excavation speed is even higher, which indicates that the cutterhead is working with more efficiency and soil on the cutterhead has a good workability. After a rapid decrease at ring 529, the thrust increased slightly at ring 610, which may be caused by the drainage and consolidation of stuck soils during excavation. The thrust dropped slightly around ring 650, the reason for this may be that sandy clay has less clay minerals, and the strength is also lower, thus clogging is reduced.

Fig. 24 (c) and Table 4 show that the average torque with Scheme 1 is 133.9% of the torque in Scheme 2. Take the torque percentage $k_T$ mentioned above as the standard, the tunneling process was in a high clogging potential with Scheme 1.

In summary, the thrust, torque and excavation speed of tunneling showed that, the new soil conditioning scheme performed better than the old one. Clogging has been reduced with the new soil conditioning scheme.

Fig. 25 showed the cutterhead after the excavation. It can be seen that the clogging is not serious with the new soil conditioning scheme,
Validation by Hobart-ATUR method.
The methodology in this study can be considered as a further study based on previous studies (Thewes, 1999; Zumsteg and Puzrin, 2012; Hollmann and Thewes, 2010; Oliveira et al., 2019) by enabling the study of tunnelling parameters in laboratory with in-situ soil. The methodology proposed a laboratory routine to check the possibility of clogging during tunnelling by monitoring tunnelling parameters. It is also feasible to describe the clogging process inside the shield machine. The field validation shows that this methodology can be used to forecast the TBM performance by performing tests with in-situ soils. The test results were compared with the Hobart-ATUR method (Oliveira et al., 2019) as a validation based on Eq. (4), Eq. (5) and Eq. (6), as shown in Table 5.

The table shows that the clogging potential as evaluated by the method in Oliveira et al. (2019) is lower. The possible reason is that the Hobart-ATUR method is performed at atmospheric pressure. In shield tunneling, the drainage and consolidation of the soil under pressure may increase the clogging potential. This increase of clogging potential seems to be more obvious with increasing excavation duration, as shown in Fig. 11 and Fig. 15.

The free fall procedure in this study was performed on a wooden base to protect the cutting device. Thus, the free fall data in Fig. 18 and Fig. 19 cannot be compared with the Hobart-ATUR method directly due to different free fall height and base. Despite the differences above, the Hobart-ATUR method shows same trend of clogging reduction with increasing FIR. The Hobart-ATUR method is valuable due to its easiness of reproduction both in the laboratory and on the job site. The proposed method in this study which can simulate actual tunnelling to some extent can be used together with Hobart-ATUR method as a validation. Both two methods need further validation with actual tunnel projects.

It should be noticed that the soil conditioning scheme with lowest torque and excavation speed during the tests may not be suitable in actual tunnelling. For example, tests with FIR 100% and 120% have lower torque and higher excavation speed as the conditioned soil has strong fluidity and compressibility. In practice, excess foam in the soil will move to the top of the pressure chamber and form an air pocket, once air in the air pocket is released, the support pressure would be insufficient, soil and water ahead of the shield machine would flow into chamber, causing ground volume loss and excess surface settlement (Alavi Gharahbagh et al., 2013; Mori et al., 2015; Fang et al., 2019; Oliveira et al., 2019).

It should be also addressed that the in-situ clogging mentioned in this study occurred in soil with low clay content. The clogging occurred is mainly because the possibility of clogging was overlooked for this low clay content soil, rather than the high clogging potential. Therefore, regular foam was used instead of anti-clay polymer or dispersant. To ensure the effect of soil conditioning, the construction company decided to use the concentration of 3.5% between Ring 528 and Ring 760 as old buildings are densely distributed in this section. The results show the new soil conditioning scheme was quite effective. However, using the concentration of 3.5% results in a higher cost. The concentration was reduced to the widely used value 3% in other sections of the project. Lower concentration may still be effective, yet the construction company wanted to guarantee the effect of soil conditioning, the value 3% (recommended by the chemical supplier) was then chosen.

The position of soil tested in the universal clogging assessment diagram is shown in Fig. 1. To get a better soil conditioning performance, the consistency index of soil should be kept away from the high clogging potential area. Maidl et al. (2012) pointed out that the consistency index of soil inside the shield machine should be 0.4-0.75 to support the tunnel face. Thewes and Budach (2010) mentioned the soil index lower

<table>
<thead>
<tr>
<th>FIR (%)</th>
<th>λ₀</th>
<th>λ₁</th>
<th>λ₂</th>
<th>λ₃</th>
<th>λ₄</th>
<th>CB_{Hobur}</th>
<th>λₑ</th>
<th>Clogging category</th>
<th>Clogging risk (Speed)</th>
<th>Clogging risk (Torque)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.233</td>
<td>0.231</td>
<td>0.232</td>
<td>0.231</td>
<td>0.078</td>
<td>2.0</td>
<td>0.101</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>20</td>
<td>0.103</td>
<td>0.103</td>
<td>0.103</td>
<td>0.103</td>
<td>0.085</td>
<td>2.0</td>
<td>0.050</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>40</td>
<td>0.096</td>
<td>0.096</td>
<td>0.096</td>
<td>0.096</td>
<td>0.053</td>
<td>2.0</td>
<td>0.044</td>
<td>Low</td>
<td>Medium</td>
<td>High/Medium</td>
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<tr>
<td>60</td>
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<td>0.091</td>
<td>0.091</td>
<td>0.089</td>
<td>0.039</td>
<td>2.0</td>
<td>0.040</td>
<td>Low</td>
<td>Medium/Low</td>
<td>Low</td>
</tr>
<tr>
<td>80</td>
<td>0.087</td>
<td>0.073</td>
<td>0.032</td>
<td>0.026</td>
<td>0.016</td>
<td>2.0</td>
<td>0.023</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>100</td>
<td>0.085</td>
<td>0.070</td>
<td>0.030</td>
<td>0.022</td>
<td>0.013</td>
<td>2.0</td>
<td>0.022</td>
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<td>Low</td>
</tr>
<tr>
<td>120</td>
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<td>0.072</td>
<td>0.029</td>
<td>0.022</td>
<td>0.014</td>
<td>2.0</td>
<td>0.022</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
than 0.4 is not recommended since the pressure-tightness of the screw conveyor cannot be ensured. Fig. 1 shows that the soil tested in this study is in a strong clogging category, yet the injection of water may result in a consistency index lower than 0.4 due to the low plastic limit. Thus, the tested soil was not conditioned with water or foam with very low FER (5–8). For soils with high clay contents and high plastic limits, regular foam with low FER (5–8) should be used. In the same scenario, water, dispersant and foam with anti-clay polymer could be more effective than regular foam when dealing with the clogging problem.

The major limitation of this study is the absence of foam injection device during the laboratory tests. Due to this limitation, conditioned soil should be used instead of unconditioned soil with a foam injection device. Conditioned soils were filled in a loose form, instead of filled at a certain density. During actual tunnelling, foam cannot penetrate into cohesive soils ahead of the cutterhead due to the low permeability, soils enter the excavation chamber as lumps, as pointed out by Ferlai et al. (2016). In the excavation chamber and the screw conveyor, the excavated soil and foam are further mixed, making the soil-foam mixture closer to the conditioned soil used in this study. Thus, the soil distribution shown in Fig. 16 and Fig. 17 is closer to the soil distribution behind the cutterhead, where holes also exist. The actual clogging at the front of the cutterhead should be more serious. The excavation speed shown in Fig. 10, can be used to prove this statement. Fig. 10 shows that the average speed of Stage III and Stage II is near, an obvious difference of average speed between these two stages was not found as expected. The reason is, in laboratory tests, the conditioned soil can be squeezed out due to the insufficient shear strength of the well mixed conditioned soil, the excavation speed can then remain constant. In actual tunnelling, the soil lumps at the front of the cutterhead may be compressed, more serious clogging may occur due to the drainage and consolidation, the average speed will then significantly decrease.

The absence of foam injection device also influences the pressure chosen during the laboratory tests. The thrust on the job site mentioned in this study is around 14 MN and the diameter of the cutterhead is 6 m, making the pressure acted on the cutterhead around 0.5 bar while the pressure during the laboratory tests was 3 bar. The big pressure difference over the cutting device is to shorten the duration of the tests within the half-life time of foam. As foam is more stable in soil-foam mixture (Wu et al. 2020) and drainage is slower under high pressure (Wu et al. 2018), foam during the tests can then be regarded stable. In actual tunnelling, the high pressure may lead to higher effective stress, speed up the drainage and the consolidation of the soil, thereby making clogging more serious.

Another limitation is the saturated soil used in foam loss test. The mixture in the foam loss test is mud-like, it is not suitable for EPB tunnelling as the flowability is too high. When mixing soil and foam in unsaturated cohesive soils, the soil particles will absorb water from the liquid film of bubbles and reduce the stability of foam. Besides, effective stress will show when pressurizing unsaturated cohesive soils. Thus, the foam loss test is only an attempt on how to mix cohesive soil with foam in a laboratory, more work should be done to simulate the foam mixing in cohesive soil with accuracy. This difficulty makes mixing the cohesive soil and foam with foam injection device a better solution when simulating actual tunneling in laboratory.

The tests in this study used recycled soil. Although test results show that the recycle did not influence the repeatability of the laboratory tests, it is not likely to remove all the additives.

The clogging monitoring and the clogging process brought up in this study need to be further validated to be widely used. More applications of the proposed method in actual tunnel projects are needed as back analysis. In actual shield tunnelling, the clogging is influenced by many factors, such as the soil properties, underground water, soil conditioning, the design of TBM machine and the TBM driver. The proposed method in this study should be used together with the Hobart-ATUR proposed by Oliveira et al. (2019) and the universal clogging evaluation diagram proposed by Hollmann and Thewes (2012, 2013) to ensure the accuracy.

7. Conclusions

The torque and excavation speed of a simplified laboratory tunnelling model were tested and analyzed. The conditioned soil with various FIRs was tested. It was found that clogging can be divided into three stages, the initial stage at the beginning, the stable and harmless adhesion, and the clogging. The speed percentage $k_k$ and torque percentage $k_T$ based on the second stage were proposed as a method to evaluate the potential of clogging. When $k_k$ is lower than 70% or $k_T$ is higher than 112.5%, the tunnelling has a high clogging potential.

The pictures of cutting device after excavation were analyzed. The soil distribution on the cutting device shows that, clogging first occurs by covering cutters, then by filling the interval between cutters, and finally by blocking the opening. Clogging is most likely to occur at the central part of the cutting device, thus the opening at the center of the cutting device is of vital importance.

An engineering application was analyzed based on Guangzhou Metro Line 21. The in-situ data shows that with the soil conditioning scheme proposed in this paper, the thrust and torque of the shield machine were reduced, and the excavation speed increased, indicating the clogging on cutterhead was significantly reduced. After the shield machine enters sandy clay from completely decomposed granite, the torque and thrust are reduced, indicating that clogging is closely related to the clay minerals in the soil. The picture of cutterhead after excavation shows that, the clogging on the center of the cutterhead is relatively serious. This once again proves that the opening at the center of the cutterhead is crucial.

CRediT authorship contribution statement


Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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