Front. Struct. Civ. Eng. 2025, 19(3): 411–426
https://doi.org/10.1007/s11709-025-1159-6

RESEARCH ARTICLE

# Laboratory and field tests on soil conditioning for earth pressure balance shield tunneling in composite strata with different sand–rock ratios

**Kangjian ZHANG[a,b], Zhiqiang ZHANG[a,b*], Chuanxiang LIU[a,b]**

[a] *State Key Laboratory of Intelligent Geotechnics and Tunnelling, Southwest Jiaotong University, Chengdu 610031, China*
[b] *School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China*
[*] *Corresponding author. E-mail: clarkchang68@163.com*

© Higher Education Press 2025

**ABSTRACT** The excavated soil in the chamber of an earth pressure balance (EPB) shield is typically required to achieve a plastic flow state during tunneling to ensure a stable excavation face and the smooth discharge of soil. When EPB shield tunneling takes place in composite strata with gravelly sand above and moderately weathered argillaceous siltstone with high clay mineral content below, the changing sand–rock ratio on the excavation face leads to a greater risk of water spewing and clogging on the cutterhead, posing enormous challenges to soil conditioning. In the study reported here, we used foam and bentonite slurry as conditioning materials for mixed soil. A series of laboratory tests were performed on the conditioned soil with different sand–rock ratios and water contents to determine the optimal injection ratios of conditioning materials. A miniature EPB shield model test involving soil pressure balance, conditioning material injection, and tunneling control was conducted to simulate the continuous excavation process from full-face sand to full-face rock stratum. The model and field test results of thrust, torque, and soil pressure in the soil chamber and screw conveyor validate the effectiveness of the proposed soil conditioning schemes for composite strata with different sand–rock ratios. The test results indicate that the volume ratio 4:1 of foam to bentonite slurry achieves better performance of the conditioned gravelly sand at a lower total injection ratio ($TIR$ < 10%). The bentonite slurry has a significant improvement effect on the flow plasticity of crushed moderately weathered argillaceous siltstone. The influence of bentonite slurry on the slump value of conditioned soil is greater than that of foam. Based on the optimal injection ratios of conditioning materials for full-face sand ($\phi = \infty$) and full-face rock ($\phi = 0$), the injection ratios for composite strata were obtained by weighted summation according to the area ratio of different strata on the tunnel face. This research provides valuable insights into soil conditioning and parameter determination methods for EPB shield tunneling in composite strata.

**KEYWORDS** soil conditioning, earth pressure balance shield, composite strata, sand–rock ratio, model test

## 1 Introduction

Full-face earth pressure balance (EPB) shield machines have increasingly been used in urban subway construction in China in recent years, as they have advantages such as high excavation efficiency and a small impact on the surrounding environment [1,2]. An important prerequisite for normal tunneling using an EPB shield is that the excavated soil is in a plastic flow state. This ensures there is a stable excavation face, a smooth discharge of the soil, and the occurrence of water spewing from the screw conveyor and clogging on the cutterhead is prevented [3,4]. This plastic flow state of the excavated soil is mainly characterized by small cohesion and internal friction angle, low permeability, high flowability, and good water retention [5–7]. The unconditioned soil generally cannot fully meet the above requirements. Hence, injecting water, foam, bentonite slurry, polymer, and other materials is often necessary to condition the excavated soil during shield machine tunneling.

*Article history: Received May 13, 2024; Accepted Oct 27, 2024*

Many scholars have conducted experimental research on soil conditioning in EPB shield tunneling, mainly focusing on the following four aspects: 1) the action mechanism of additives to conditioned soil [8–11]; 2) the research and development of new conditioning materials [1,12,13]; 3) the effects of the properties and injection ratio of the conditioning materials on the various plastic-flow indexes of conditioned soil [14–17]; 4) the effect of soil conditioning on the EPB shield tunneling parameters [18,19]. The strata studied include water-rich sand, sand-pebble stratum, clay, argillaceous siltstone, limestone, and marl layers, etc. Hu et al. [20], Huang et al. [21], and Wang et al. [22,23] studied the permeability characteristics of foam-conditioned sand in different conditioning states for mechanized tunneling. Xu et al. [19], Huang et al. [24], and Wang et al. [25] carried out laboratory tests on conditioned sandy-cobble soil and evaluated the workability of conditioned soil. Peila et al. [26] and Todaro et al. [27] studied the dynamic adhesion of conditioned clayey soil.

The research results described above provided many effective means and a theoretical basis for understanding the mechanical properties of sandy or clay-based soil. However, most of the studies were focused on a single homogeneous stratum, and there are few reports on soil conditioning for composite strata. The composite strata with sand above and rock below, especially where the lower part is weathered rock with high clay mineral content, are experienced frequently during EPB shield tunneling. This sand–rock composite strata (referred to in this study as a rock with high clay mineral content) combines the dual characteristics of sand and clay layers, and the performance of mixed soil in the soil chamber has a particularly significant impact on excavation safety [28]. When the sand layer accounts for a larger proportion of the excavation face, problems such as instability of the excavation face and water spewing are likely to occur. When the rock dominates the excavation face, issues such as low excavation speed, abnormal cutter wear, and clogging on the cutterhead and cutters are likely to occur [6]. The composite ratio of the two strata on the excavation face does vary in shield tunneling. The changing sand–rock ratio on the excavation face leads to a greater risk of water spewing and clogging on the cutterhead, posing enormous challenges to soil conditioning. Consequently, the conditioning material injection schemes for a single stratum cannot be applied ideally in actual EPB shield tunneling in composite strata. Therefore, the soil conditioning methods for sand–rock composite strata require further discussion.

As conventional soil conditioning tests and evaluation methods cannot truly reflect the characteristics of the undisturbed soil and the construction environment, the test results are difficult to apply to actual construction directly. Some researchers have begun to incorporate model tests to evaluate the soil conditioning effectiveness based on thrust, torque, and other tunneling parameters [4,29]. Hu and Rostami [30,31] found the interdependency between soil conditioning settings and rheological parameters in the conditioned soil using the soil rheology evaluation system developed at the Colorado School of Mines. Lee et al. [32] proposed a laboratory-scale experimental approach to evaluate the rheological properties of conditioned soil. Currently, the model test devices available for EPB shield tunneling with simultaneous soil conditioning are very limited and do not have rich functions. The model test combining conditioning material injection and EPB shield tunneling control while evaluating the soil conditioning effect with tunneling parameters needs further research.

In summary, the above literature review indicates that few studies focused on soil conditioning for composite strata and the effect of sand–rock ratio. In addition, there is no research on the model test combining conditioning material injection and tunneling parameter control. In view of this, this study highlights the soil conditioning for EPB shield tunneling in the gravelly sand and moderately weathered argillaceous siltstone composite strata with different sand–rock ratios. We used foam and bentonite slurry as conditioning materials. A series of laboratory tests were performed on conditioned soil with different sand–rock ratios and water contents to determine the optimal injection ratios of conditioning materials. A model test system using a miniature EPB shield was upgraded to realize the full range of functions of conditioning material injection and tunneling control. The soil conditioning effect and the variability of tunneling parameters in strata with different sand–rock ratios were investigated through model and field tests.

## 2 Materials description

### 2.1 Sand and rock

The gravelly sand and moderately weathered argillaceous siltstone used in the laboratory tests are collected from the engineering site of the Nanchang Rail Transit Line 4, Jiangxi Province, China. Geological investigation shows that the EPB shield excavates for long distances in composite strata of gravelly sand and moderately weathered argillaceous sandstone, which puts higher requirements on the effectiveness of soil conditioning.

The gravelly sand is yellowish-brown, saturated, and medium-dense, with a natural density of 2.0 g/cm$^3$ and a saturated water content of 20.4%. The permeability coefficient of gravelly sand is $1.21 \times 10^{-3}$ m/s, and the specific gravity of sand particles is 2.63. The grain-size distribution is shown in Fig. 1. The gravelly sand samples are poorly graded sandy (SP) with a uniformity

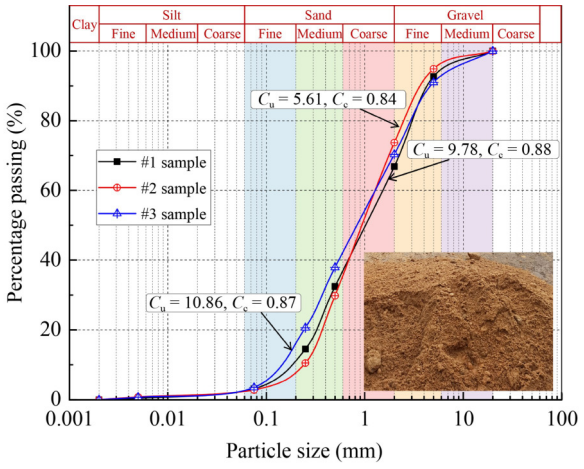



**Fig. 1** Grain-size distribution of gravelly sand.

coefficient $C_u$ of 5.61–10.86 and a curvature coefficient $C_c$ of 0.84–0.88 according to the ASTM D2488-17e1 [33] standard classification. The proportion of particles with a size of 2–20 mm in the soil sample is 29.7%–33.2%, and the fine particles smaller than 0.075 mm only account for 2.8%–3.5%, which is far less than the ideal range of 20%–30%. This type of soil is extremely prone to water spewing from the screw conveyor and to excavation face instability due to the high permeability coefficient and poor fluidity of the soil when EPB shield tunneling in a saturated gravelly sand stratum.

The moderately weathered argillaceous siltstone of the engineering site is brownish crimson, with argillaceous cementation predominantly and calcareous cementation locally, which is easily softened by water. According to the geological investigation, the natural density and saturation density of the moderately weathered argillaceous siltstone are 2.36 and 2.42 g/cm$^3$, the natural water content is 11.2%, the permeability coefficient is $1.16 \times 10^{-6}$ m/s, and the rock quality designation is 55%–90%. The uniaxial ultimate compressive strengths of the rocks in the dry, natural, and saturated states are 21.3, 10.1, and 7.0 MPa, respectively. The mineral composition of moderately weathered argillaceous siltstone is given in Table 1. The proportion of clay minerals such as kaolinite, montmorillonite, and illite in the rock exceeds 40%. These clay minerals are important causes of clogging on the cutterhead and cutters [34].

**Table 1** Mineral composition of moderately weathered argillaceous siltstone

| Mineral | Proportion (%) |
|---|---|
| Quartz | 44.3 |
| Kaolinite | 29.1 |
| Microcline | 10.8 |
| Illite | 9.6 |
| Montmorillonite | 4.6 |
| Albite | 1.6 |

## 2.2 Conditioning materials

Different conditioning materials have different stratum adaptability. The commonly used conditioning materials in actual engineering include water, foam agents, dispersants, clay minerals, and flocculants. Some researchers have developed new high-performance conditioning materials for specific strata. For example, Lu et al. [12] proposed a novel dispersed foaming agent suitable for silty clay strata by combining a surfactant, dispersant, and tackifier in proportion. Foam and bentonite slurry, commonly used in actual engineering due to their low costs and wide stratum adaptability, were used as conditioning materials in this study.

Foam is in a typical gas–liquid two-phase unstable state, with about 90% air and about 10% foam agent solution. The properties of foam, such as foaming formation and stability, are very important for improving soil discharge and maintaining pressure at the excavation face [35]. The foam expansion ratio (FER) and half-life time (H-T) are important parameters reflecting the quality of the foaming agent and the performance of the foam [6,36,37].

The mass ratio of foam agent to solution is defined as the concentration of foam agent solution, denoted by the symbol $\alpha$. Foam agent solutions with $\alpha$ = 1%, 2%, 3%, 4%, and 5% were prepared, the FER and H-T were tested, and the test results are shown in Fig. 2. It can be seen from the figure that the concentration of foam agent solution has an important impact on the stability of foam, and the FER and H-T both increase with the increase of concentration. When the concentration of foam agent solution is low ($1\% < \alpha < 2\%$), the FER and H-T slowly increase with the increase in concentration. When the concentration increases from 2% to 3%, the FER and H-T increase rapidly. When the concentration exceeds 3%, the change of FER and H-T tends to be stable. Therefore, the concentration of foam agent solution should not be too

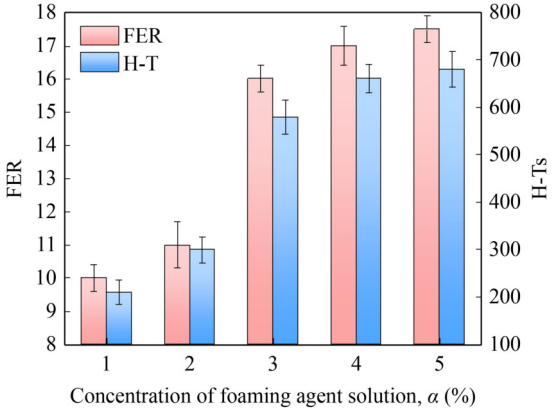



**Fig. 2** FERs of foam agent solution with different concentrations and foam's H-Ts.

high, or it will cause waste. When $\alpha$ = 3%, the foam expansion ratio is 16, and the half-life time of foam is 580 s, which matches the engineering experience (FER = 10–20 and H-T > 5 min) and the guidelines from the European Federation for Specialist Construction Chemicals and Concrete Systems for soft ground tunneling. Therefore, the concentration of the foam agent solution in this study was set to 3%.

Bentonite slurry is made by mixing bentonite and water. Viscosity and specific gravity are two important indicators for evaluating slurry performance. The mix ratio $\beta$ is defined as the mass ratio of water to dry bentonite. Taking sodium bentonite as the research object, bentonite slurries with $\beta$ = 5,6,…,14,15 were prepared, the viscosity and specific gravity of bentonite slurries with different mix ratios were tested, and the test results are shown in Fig. 3.

As can be seen from Fig.3, the funnel viscosity of the bentonite slurry increases continuously with the increase of hydration time, and the viscosity of the slurry gradually reaches a stable state after hydration for 18–24 h. Over the same hydration time (24 h), the viscosity of the bentonite slurry decreases as the mix ratio increases. When $10 < \beta < 15$, the apparent viscosity of the slurry is lower than 15 mPa·s, the plastic viscosity is less than 10 mPa·s, the specific gravity is 1.16–1.15, and the slurry is relatively thin with a layering phenomenon after slurrying. As $\beta$ reduces further, the layering phenomenon gradually disappeared, and the viscosity increased significantly. When $\beta < 5$, the apparent viscosity reaches 30 mPa·s, the plastic viscosity is > 20 mPa·s and there are water-insoluble clumps. When $\beta$ = 8, the viscosity and specific gravity of the bentonite slurry can meet the engineering needs. After comprehensive comparison, a mixing ratio of 8 and a hydration time of 24 h are selected as the slurry preparation parameters for subsequent experiments.

## 3 Laboratory tests on soil conditioning

### 3.1 Devices and procedures

Laboratory tests were conducted on gravelly sand, moderately weathered argillaceous siltstone, and mixed soil using foam and bentonite slurry. The optimal injection ratios of conditioning materials for saturated gravelly sand, moderately weathered argillaceous siltstone with different water contents, and mixed soil with different sand–rock ratios were analyzed through a series of laboratory tests. The effects of the total injection ratio (*TIR*) of the conditioning materials and the volume ratio $\zeta$ of foam and bentonite slurry on the performances of conditioned soil were studied. The tests on conditioned soil are shown in Fig. 4. The slump test, direct shear test, and constant head permeability test were conducted in accordance with ASTM C143/C143M-20 [38], ASTM D3080-04 [39], and GB/T 50123-2019 [40] specifications, respectively.

The rock samples of moderately weathered argillaceous siltstone were first crushed by a laboratory jaw crusher with the aim of preparing irregular grains similar to those in the real chamber of the EPB shield. As reported by Peila et al. [4,5,41], rock fragments or grains larger than 20 mm have almost no effect on the formation of clogging on the cutterhead and cutters. Therefore, these grains were removed from the samples. In the crushed moderately weathered argillaceous siltstone, the contents of the particles with diameters in the ranges of < 1, 1–5, 5–10, and 10–20 mm are approximately 6%–20%, 21%–32%, 27%–33%, and 21%–40%, respectively. Previous research [4,17] has shown that such grain-size distributions in samples are acceptable to characterize the soils in the chamber of the EPB shield when tunneling in moderately weathered argillaceous siltstone. The crushed moderately weathered argillaceous siltstone has high cohesion, with a liquid limit of 27.9% and a plastic limit

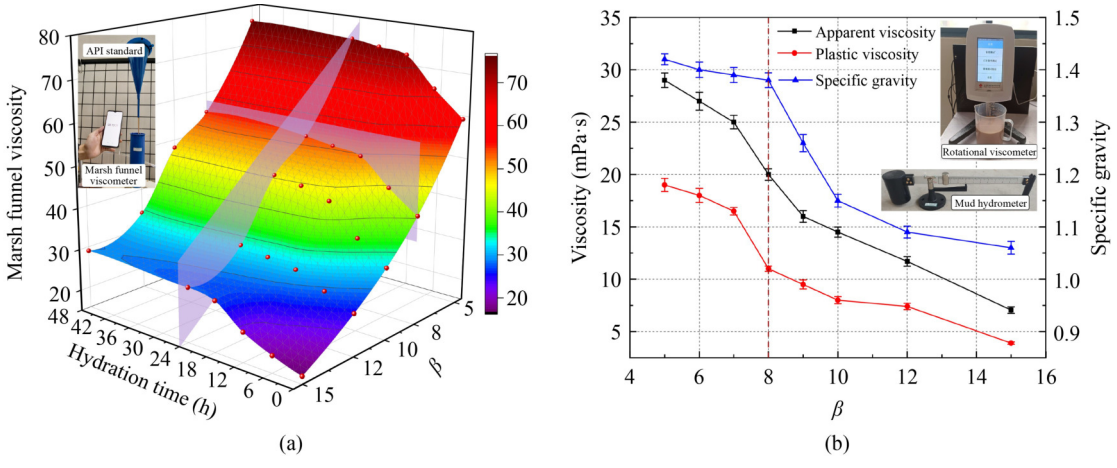



**Fig. 3** Properties of bentonite slurry: (a) Funnel viscosity; (b) apparent viscosity, plastic viscosity, and specific gravity.

of 18.4%. So, the plasticity index is 9.5, and the soil is classified as clay.

Considering the water-sensitive characteristics of clay, soil samples crushed from moderately weathered argillaceous siltstone with water contents of 18%, 20%, and 22% were prepared for the conditioning test. For the gravelly sand to be conditioned, water was added to achieve a saturated water content of 20.4%. For each *TIR*, it was subdivided into foam only, bentonite slurry only, $\zeta$ = 1: 4, $\zeta$ = 2: 3, $\zeta$ = 3: 2, and $\zeta$ = 4: 1 test cases. The conditioning cases of crushed moderately weathered argillaceous siltstone with water contents of 18%, 20%, and 22% are listed in Table 2. The conditioning cases of saturated gravelly sand are listed in Table 3. The volume ratio of foam to soil to be conditioned is defined as the injection ratio of foam, denoted by the symbol *FIR*. The volume ratio of bentonite slurry to the soil to be conditioned is defined as the injection ratio of bentonite slurry, denoted by the symbol *BIR*. Three parallel tests for each group were carried out, and the average value was used as the final experimental result.

### 3.2 Conditioning results on gravelly sand

Slump test results of conditioned, saturated, gravelly sand are shown in Figs. 5 and 6, where the following points can be observed.

1) When only foam is used, the slump value of the conditioned soil increases with the increase of *FIR*. Foam wrapping the soil particles reduces the contact area and

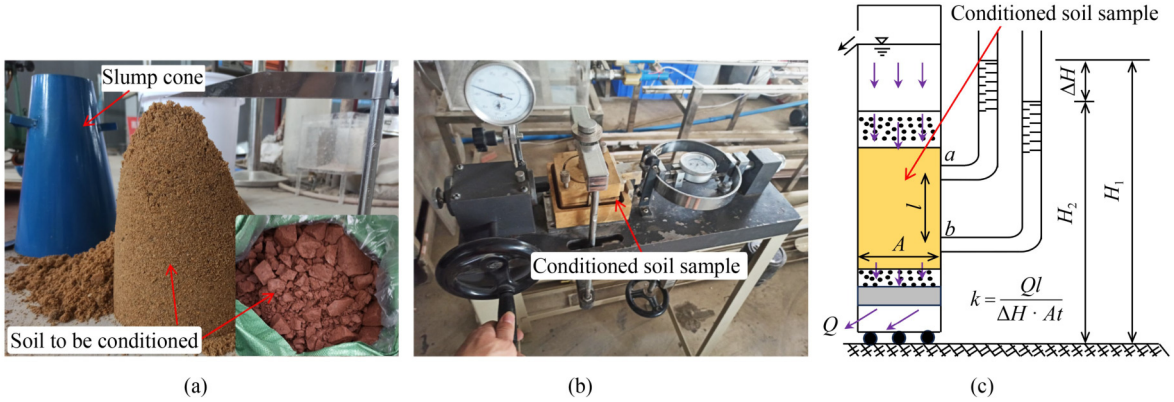



**Fig. 4** Tests on conditioned soil: (a) slump test; (b) direct shear test; (c) constant head permeability test.

**Table 2** Conditioning cases of crushed moderately weathered argillaceous siltstone with a water content of 18%, 20%, and 22%, respectively

| Case | *TIR* = 2% | | *TIR* = 4% | | *TIR* = 6% | | *TIR* = 8% | | *TIR* = 10% | | *TIR* = 12% | | *TIR* = 14% | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *FIR* | *BIR* | *FIR* | *BIR* | *FIR* | *BIR* | *FIR* | *BIR* | *FIR* | *BIR* | *FIR* | *BIR* | *FIR* | *BIR* |
| Foam only | 2 | 0 | 4 | 0 | 6 | 0 | 8 | 0 | 10 | 0 | 12 | 0 | 14 | 0 |
| Bentonite slurry only | 0 | 2 | 0 | 4 | 0 | 6 | 0 | 8 | 0 | 10 | 0 | 12 | 0 | 14 |
| $\zeta$ = 1:4 | 0.4 | 1.6 | 0.8 | 3.2 | 1.2 | 4.8 | 1.6 | 6.4 | 2 | 8 | 2.4 | 9.6 | 2.8 | 11.2 |
| $\zeta$ = 2:3 | 0.8 | 1.2 | 1.6 | 2.4 | 2.4 | 3.6 | 3.2 | 4.8 | 4 | 6 | 4.8 | 7.2 | 5.6 | 8.4 |
| $\zeta$ = 3:2 | 1.2 | 0.8 | 2.4 | 1.6 | 3.6 | 2.4 | 4.8 | 3.2 | 6 | 4 | 7.2 | 4.8 | 8.4 | 5.6 |
| $\zeta$ = 4:1 | 1.6 | 0.4 | 3.2 | 0.8 | 4.8 | 1.2 | 6.4 | 1.6 | 8 | 2 | 9.6 | 2.4 | 11.2 | 2.8 |

Note: *TIR* = *FIR* + *BIR*.

**Table 3** Conditioning cases of saturated gravelly sand with 20.4% water content

| Case | *TIR* = 5% | | *TIR* = 10% | | *TIR* = 15% | | *TIR* = 20% | | *TIR* = 25% | | *TIR* = 30% | | *TIR* = 35% | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *FIR* | *BIR* | *FIR* | *BIR* | *FIR* | *BIR* | *FIR* | *BIR* | *FIR* | *BIR* | *FIR* | *BIR* | *FIR* | *BIR* |
| Foam only | 5 | 0 | 10 | 0 | 15 | 0 | 20 | 0 | 25 | 0 | 30 | 0 | 35 | 0 |
| Bentonite slurry only | 0 | 5 | 0 | 10 | 0 | 15 | 0 | 20 | 0 | 25 | 0 | 30 | 0 | 35 |
| $\zeta$ = 1:4 | 1 | 4 | 2 | 8 | 3 | 12 | 4 | 16 | 5 | 20 | 6 | 24 | 7 | 28 |
| $\zeta$ = 2:3 | 2 | 3 | 4 | 6 | 6 | 9 | 8 | 12 | 10 | 15 | 12 | 18 | 14 | 21 |
| $\zeta$ = 3:2 | 3 | 2 | 6 | 4 | 9 | 6 | 12 | 8 | 15 | 10 | 18 | 12 | 21 | 14 |
| $\zeta$ = 4:1 | 4 | 1 | 8 | 2 | 12 | 3 | 16 | 4 | 20 | 5 | 24 | 6 | 28 | 7 |

Note: *TIR* = *FIR* + *BIR*.

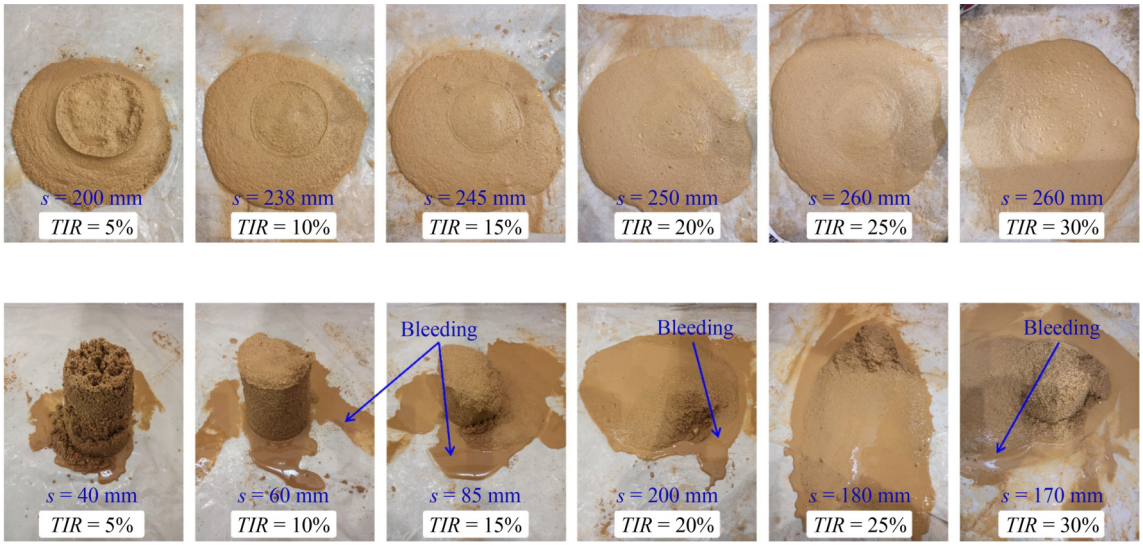



**Fig. 5** Results of slump tests carried out on saturated gravelly sand using a single conditioning material: (a) foam only; (b) bentonite slurry only.

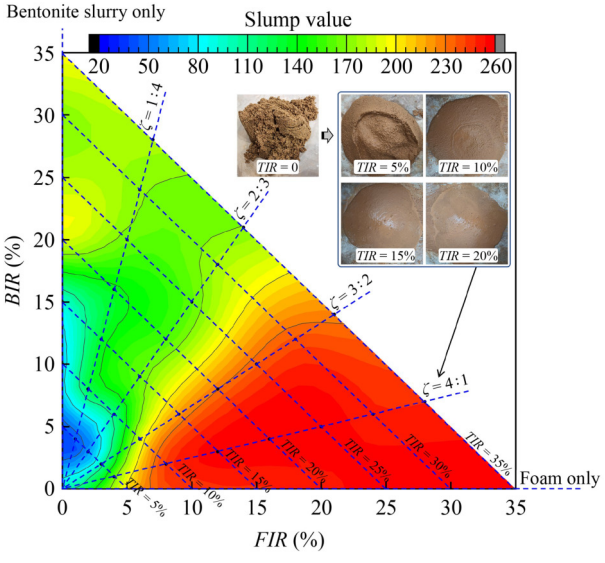



**Fig. 6** Slump results of conditioned saturated gravelly sand.

friction between particles, resulting in a significant improvement of the fluidity. However, when $FIR > 5\%$, the slump value of the conditioned soil is too large, reaching 200–260 mm. The fluidity of the soil is obviously too high, with poor cohesion, which is not conducive to the smooth discharge from the screw conveyor.

2) When only bentonite slurry is used, the minimum slump value of conditioned soil occurs at $BIR = 5\%$. The probable reason for this is that the gravelly sand itself has very little cohesion, and a certain amount of bentonite slurry can bond the sand particles. Subsequently, the slump value of conditioned soil increased slowly with increasing *BIR*, and the growth trend of slump value is significantly slower compared to the case of foam only. This indicates that the bentonite slurry is not as effective as foam in improving the fluidity of gravelly sand.

When $BIR > 17.5\%$, the slump value of the conditioned soil can reach the desired target (150–200 mm), but there are obvious bleeding and loose collapse phenomena, which indicate that the cohesion of the conditioned soil has been improved, but the water retention is insufficient. Therefore, only using bentonite slurry for conditioning can achieve certain improvements, but the effect on water-rich sand is not satisfactory enough.

3) When $\zeta$ = 1:4, 2:3, and 3:2, the slump values are 50–170 mm, 30–182 mm, and 86–240 mm, respectively, and the changing trend of the slump value is similar to the case of bentonite slurry only. When $\zeta$ = 4:1, the slump values are 185–260 mm, and the changing trend is similar to the case of foam only.

If we aim to minimize *TIR* to reduce the cost and maximize good workability of the conditioned soil, after extensive comparisons of various combinations of conditioning material injection, it was found that $\zeta$ = 4:1 can achieve better performance of the conditioned soil at a lower *TIR* ratio ($TIR < 10\%$). Therefore, the volume ratio of foam to bentonite slurry was determined as 4:1. The test results of conditioned saturated gravelly sand with different *TIR*s at $\zeta$ = 4:1 are shown in Fig. 7. When $1\% \leqslant TIR \leqslant 10\%$ and $\zeta$ = 4:1, the following observations can be made.

1) The slump value of the conditioned soil increases approximately linearly with increasing *TIR*, with a goodness-of-fit of 0.9868 and a range of 142–210 mm.

2) The internal friction angle of the conditioned soil decreases approximately linearly with increasing *TIR*, with a goodness-of-fit of 0.9812. The internal friction angle decreases by an average of 0.85° for every 1% increase in *TIR*. The conditioning materials reduce the shear strength and internal friction angle of the sand, which will reduce the torque of the EPB shield and cutter/cutterhead wear.

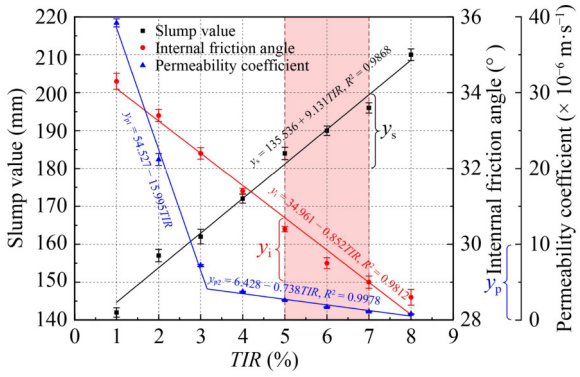



**Fig. 7** Test results of conditioned saturated gravelly sand with different *TIR*s at $\zeta = 4$: 1.

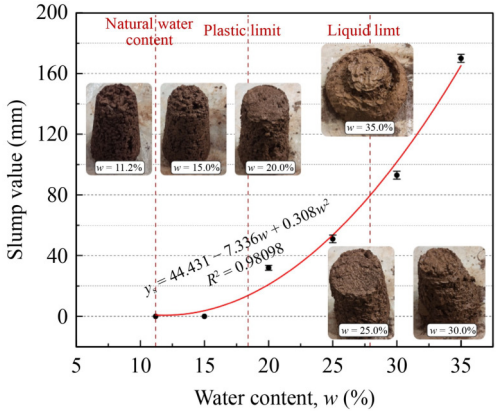



**Fig. 8** Curve of slump versus water content for moderately weathered argillaceous siltstone without conditioning.

3) The permeability coefficient of the conditioned soil reaches a magnitude in the order of −6 to −5, which is significantly lower than that before conditioning and can effectively reduce the risk of water spewing during EPB shield tunneling. The permeability coefficient is affected considerably by the *TIR* at *TIR* < 3%, and the change curve of the permeability coefficient is gradually stabilized after *TIR* > 3%.

The goals of gravelly sand conditioning are to improve impermeability, flow plasticity, and reduce internal friction angle. Taking the factors above into consideration, it is recommended that the *TIR* of conditioning material for saturated gravelly sand be 5%–7% and the volume ratio of foam to bentonite slurry be 4: 1. At these ratios, the slump value of conditioned soil is 180–200 mm, the internal friction angle is 29.0°–30.7°, and the permeability coefficient is lower than $10^{-5}$ m/s, which has met the requirements for preventing water spewing [36,42,43].

### 3.3 Conditioning results on moderately weathered argillaceous siltstone

The curve of slump versus water content for moderately weathered argillaceous siltstone without conditioning material injected is shown in Fig. 8. As can be seen from the figure, the slump value of moderately weathered argillaceous siltstone is less than 20 mm when the water content is less than the plastic limit. The slump value increases continuously with the increase of water content when the water content is greater than the plastic limit. When the water content reaches 35%, the slump value of moderately weathered argillaceous siltstone is about 170 mm. At this water content, although the slump value of soil basically meets the engineering requirements, the cohesion is still high.

Conditioning tests were carried out on crushed moderately weathered argillaceous siltstone using foam and bentonite slurry, and the slump values of conditioned soil with different water contents are shown in Fig. 9, from which the following several points can be seen.

1) When the same conditioning scheme is used, the slump value of conditioned soil increases with an increase in *TIR* and water content.

2) The bentonite slurry has a significant improvement effect on the flow plasticity of crushed moderately weathered argillaceous siltstone. The influence of bentonite slurry on the slump value of conditioned soil is greater than that of foam.

3) Due to the crushed argillaceous siltstone's better water absorption, many injected foams break down, resulting in a poor improvement in the performance of conditioned soil. Therefore, foam is not suitable for soil conditioning when using an EPB shield to excavate in moderately weathered argillaceous siltstone.

4) When the same water content and *TIR* are used, the slump value of conditioned soil decreases with the increase of *FIR*. The main reason is that the burst foam fails to condition soil, and the content of effective conditioning material in the injected material decreases at a certain *TIR*.

Previous research [17] has shown that the slump value of 170–200 mm for crushed moderately weathered argillaceous siltstone is appropriate for EPB excavation. The optimal injection ratio of conditioning material shown in Table 4 can be obtained by taking 170–200 mm as the target slump range for conditioned soil.

### 3.4 Conditioning results on sand–rock composite strata

When EPB shield tunneling in composite strata, both the upper gravelly sand and the lower moderately weathered argillaceous siltstone will appear on the excavation face simultaneously. The sand–rock ratio in this study refers to the arc height (sagitta) ratio corresponding to gravelly sand and moderately weathered argillaceous siltstone on the excavation face, represented by the symbol $\phi$. The actual EPB shield excavates from full-face sand ($\phi = \infty$) to full-face rock ($\phi = 0$) stratum. Five typical sand–rock ratios are studied here, and the tunnel faces with different

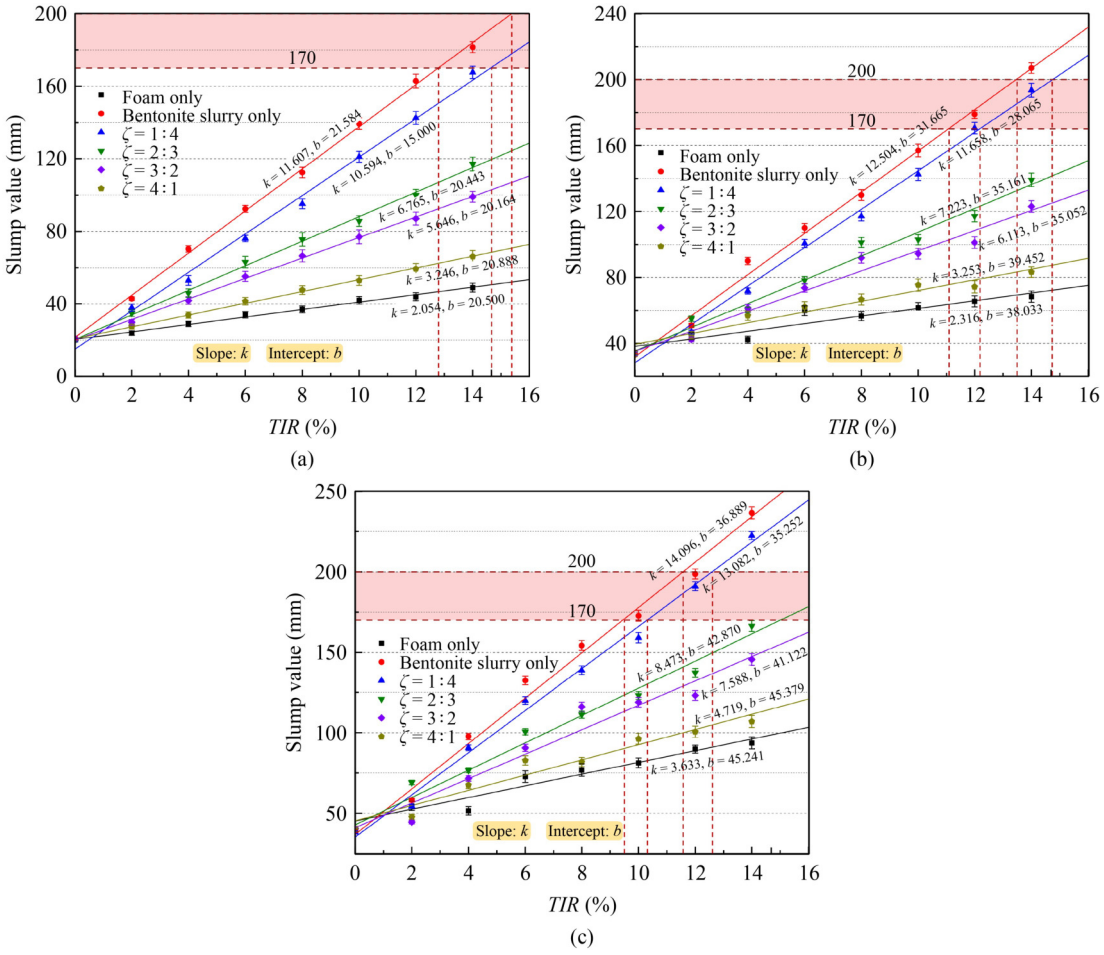



**Fig. 9** Slump values of conditioned, moderately weathered argillaceous siltstone with different water contents: (a) $w$ = 18%; (b) $w$ = 20%; (c) $w$ = 22%.

**Table 4** Injection ratios of conditioning material at the target slump value of 170–200 mm

| Water content of moderately weathered argillaceous siltstone (%) | Injection scheme | *TIR* (%) | *FIR* (%) | *BIR* (%) |
|---|---|---|---|---|
| $w$ = 18 | bentonite slurry only | 12.8–15.4 | 0 | 12.8–15.4 |
| $w$ = 20 | bentonite slurry only | 11.1–13.5 | 0 | 11.1–13.5 |
| | $\zeta$ = 1:4 | 12.2–15.4 | 2.44–3.08 | 9.76–12.32 |
| $w$ = 22 | bentonite slurry only | 9.4–11.6 | 0 | 9.4–11.6 |
| | $\zeta$ = 1:4 | 10.3–12.6 | 2.06–2.52 | 8.24–10.08 |

sand–rock ratios are shown in Fig. 10.

It is assumed that the volume ratio of the two types of soils excavated per unit distance of EPB shield advance is equal to the area ratio of the two strata on the tunnel face. Based on the above-obtained optimal injection ratios of conditioning materials for full-face sand ($\phi = \infty$) and full-face rock ($\phi = 0$), the injection ratios for composite strata can be obtained by weighted summation according to the area ratio of different strata on the tunnel face, as given in Table 5. The water content of the gravelly sand in the table is the saturated water content of 20.4%, and the water content of the moderately weathered argillaceous siltstone is either 18%, 20%, or 22%, respectively. The sand and rock samples were mixed according to the volume ratio to obtain the mixed soil, and their slump values are given in Table 5. The average values of slump are all in the range of reasonable slump 170–200 mm, which indicates that the proposed conditioning schemes and injection ratios for the composite strata are reasonable.

## 4 Miniature EPB shield model tests

The effectiveness of the conditioning scheme obtained from the laboratory tests for composite soil with different

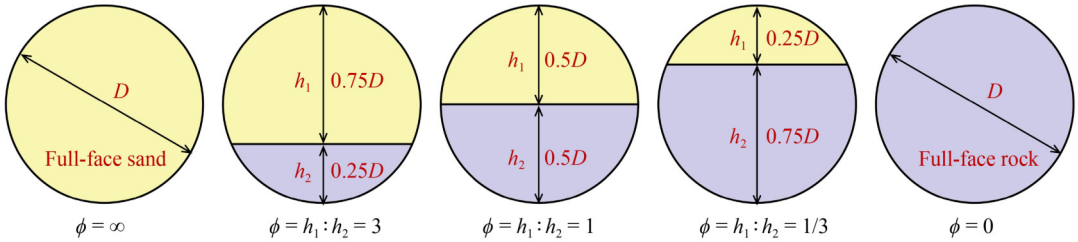



**Fig. 10** Tunnel faces with different sand–rock ratios.

**Table 5** Injection ratios of conditioning materials and corresponding slump values for composite strata

| Water content of moderately weathered argillaceous siltstone (%) | $\phi$ | *FIR* (%) | *BIR* (%) | Slump average value (mm) | Standard deviation (mm) |
|---|---|---|---|---|---|
| $w$ = 18 | 3 | 3.22–4.51 | 3.31–4.14 | 180 | 4 |
| | 1 | 2.00–2.80 | 6.90–8.40 | 173 | 2 |
| | 1/3 | 0.78–1.10 | 10.49–12.66 | 175 | 5 |
| $w$ = 20 | 3 | 3.22–4.51 | 2.97–3.77 | 188 | 6 |
| | | 3.70–5.11 | 2.71–3.53 | 190 | 4 |
| | 1 | 2.00–2.80 | 6.05–7.45 | 172 | 2 |
| | | 3.22–4.34 | 5.38–6.86 | 185 | 5 |
| | 1/3 | 0.78–1.10 | 9.13–11.13 | 175 | 3 |
| | | 2.74–3.57 | 8.05–10.19 | 174 | 4 |
| $w$ = 22 | 3 | 3.22–4.51 | 2.64–3.39 | 181 | 5 |
| | | 3.62–5.00 | 2.42–3.10 | 189 | 6 |
| | 1 | 2.00–2.80 | 5.20–6.50 | 170 | 3 |
| | | 3.03–4.06 | 4.62–5.74 | 184 | 5 |
| | 1/3 | 0.78–1.09 | 7.76–9.61 | 183 | 5 |
| | | 2.44–3.12 | 6.82–8.38 | 192 | 6 |

sand–rock ratios needs to be further verified by model tests. A miniature EPB shield test was carried out to analyze the indicators of thrust, torque, soil pressure in the soil chamber, and soil pressure in the screw conveyor during shield machine tunneling.

### 4.1 Miniature EPB shield

Zhang et al. [44] reported a full-face Tunnel Boring Machine tunneling test system. The test system comprises three primary components: soil box, propulsion, and tunneling device, as well as data sampling and control system. This test system was upgraded to include soil pressure balance and conditioning material injection, as shown in Fig. 11.

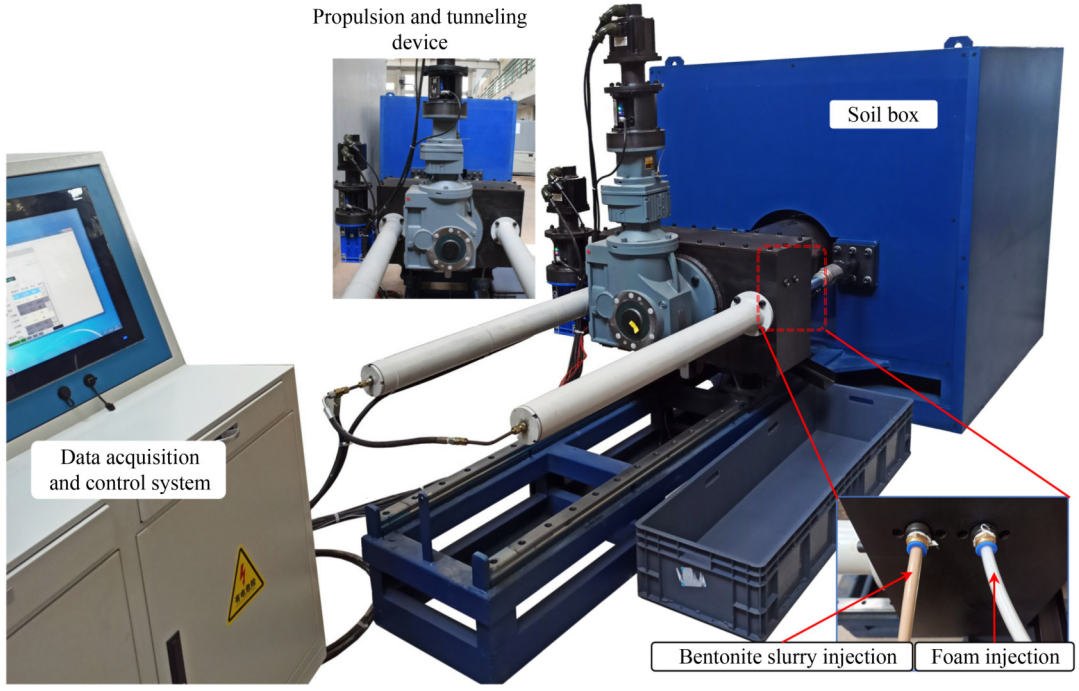
The upgraded test system has added a soil chamber, a screw conveyor, a soil pressure sensor, and a conditioning material injection system. There are two independent tubes leading to the soil chamber, which can be used to inject foam, bentonite slurry, and other materials according to requirements. Based on a geometric length similarity ratio of 20, the excavation diameter of the cutterhead is set to 314 mm, the outer diameter of the screw conveyor is set to 40 mm, and the major and minor diameters of the spiral shaft are set to 34 and 18 mm. The soil chamber and screw conveyor are equipped with a total of six soil pressure sensors, which can monitor the soil pressure during the soil conveying process. The locations of the soil pressure sensors are shown in Fig. 11(b).

The cutterhead used in the test is equipped with one star-shaped center cutter with a 19 mm tip, 24 positive cutters with 13 mm tips, and the opening ratio of the cutterhead is about 35%, which matches the actual cutterhead. Twelve stirring rods behind the cutterhead allow for the mixing of the soil and injected conditioning material. The miniature EPB shield is also equipped with various sensors, such as a pull rope displacement sensor, a force sensor, a rotary torque sensor, and a rotational speed sensor. The upgraded test system can more realistically simulate the EPB shield tunneling process and study the influence of shield operation parameters (thrust, torque, penetration rate, rotational speed of the cutterhead, screw conveyor, etc.) on the tunneling performance.

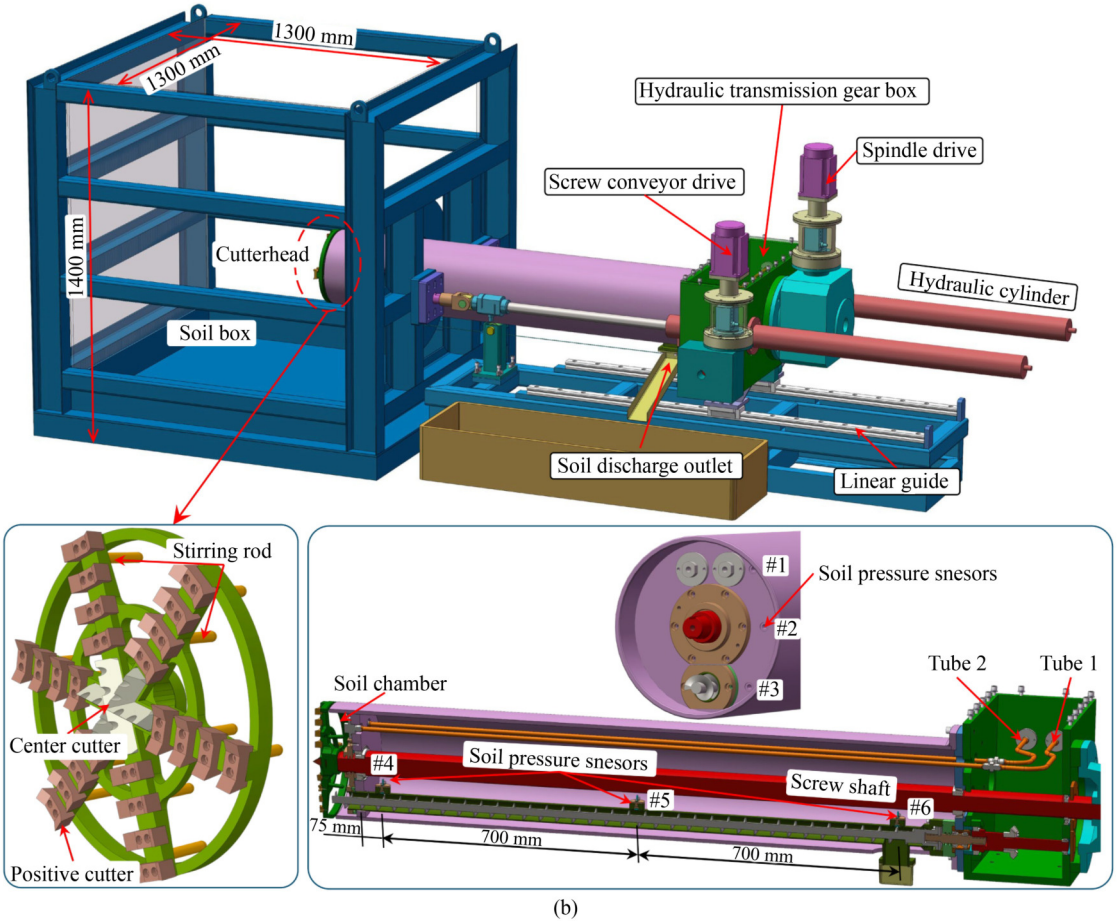
### 4.2 Scheme of model tests

The gravelly sand and moderately weathered argillaceous siltstone used in the model tests are collected from the engineering site, and they are all undisturbed soil/rock samples. The gravelly sand in the soil box is water-saturated, and the water content of the moderately weathered argillaceous siltstone is 20%. The longitudinal profile of the model soil is shown in Fig. 12. The actual EPB shield excavates from full-face sand ($\phi = \infty$) to full-face rock ($\phi$ = 0) stratum. Corresponding to field and laboratory tests, the sand–rock ratio of the model test is still typically set to ∞, 3, 1, 1/3, 0. The shield machine advances sequentially into the strata $A_1$–$E_2$ with a width of 100 mm for each type of stratum, where $A_1$–$A_2$ are full-face gravelly sand strata, $B_1$–$B_2$ are composite strata with $\phi$ = 3, $C_1$–$C_2$ are composite strata with $\phi$ = 1, $D_1$–$D_2$ are composite strata with $\phi$ = 1/3, and $E_1$–$E_2$ are full-face moderately weathered argillaceous siltstone strata.

In this research, the rotation speed of the cutterhead is set to 1.2 r/min, and the rotation speed of the screw conveyor is set to 3.0–4.0 r/min based on field




(a)




(b)

**Fig. 11** Photograph and detailed schematics of miniature EPB shield: (a) image of the upgraded test system equipment; (b) diagram of equipment configuration.

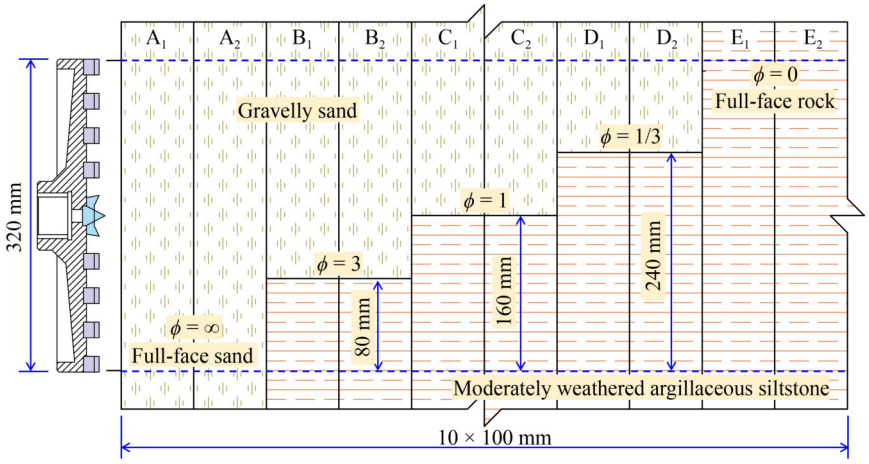



**Fig. 12** Longitudinal profile of model soil.

engineering and similarity theory [45]. Regardless of the ground volume loss caused by excavation, the injection ratios of conditioning material (i.e., *FIR* and *BIR*) obtained from the laboratory tests for different strata are converted into time-dependent injection parameters for the model tests, as given in Table 6. Based on the parameters in the table, the tunneling simulation tests are conducted using the miniature EPB shield.

**Table 6** Injection parameters of conditioning materials in model test

| Stratum | Foam ($mL \cdot s^{-1}$) | Bentonite slurry ($mL \cdot s^{-1}$) | Stratum | Foam ($mL \cdot s^{-1}$) | Bentonite slurry ($mL \cdot s^{-1}$) |
|---|---|---|---|---|---|
| $A_1$ | 2.3–3.3 | 0.5–0.8 | $A_2$ | 2.3–3.3 | 0.5–0.8 |
| $B_1$ | 1.8–2.6 | 1.6–2.0 | $B_2$ | 2.1–2.9 | 1.4–1.8 |
| $C_1$ | 1.1–1.6 | 3.2–3.9 | $C_2$ | 1.8–2.3 | 2.8–3.3 |
| $D_1$ | 0.4–0.6 | 4.7–5.8 | $D_2$ | 1.4–1.8 | 4.1–4.8 |
| $E_1$ | 1.2–1.4 | 5.0–5.9 | $E_2$ | 0 | 5.8–7.0 |

### 4.3 Test results and analyses

The thrust and torque curves of the miniature EPB shield are shown in Fig. 13, from which the following points can be seen.

1) Compared to the strata dominated by gravelly sand ($\phi > 1$), when the cutterhead is tunneling into a stratum dominated by argillaceous siltstone ($\phi < 1$), the thrust increases by approximately 6%, and the torque fluctuation decreases.

2) For strata with the same sand–rock ratio, the difference in thrust (torque) between the two conditioning material injection schemes obtained from the soil conditioning tests is not significant, verifying the accuracy of the soil conditioning tests.

3) The thrust and torque of different sand–rock ratio strata fluctuate within an acceptable range, with a relatively stable fluctuation trend, which stabilizes the tunneling parameters and verifies the effectiveness of the soil conditioning schemes proposed above.

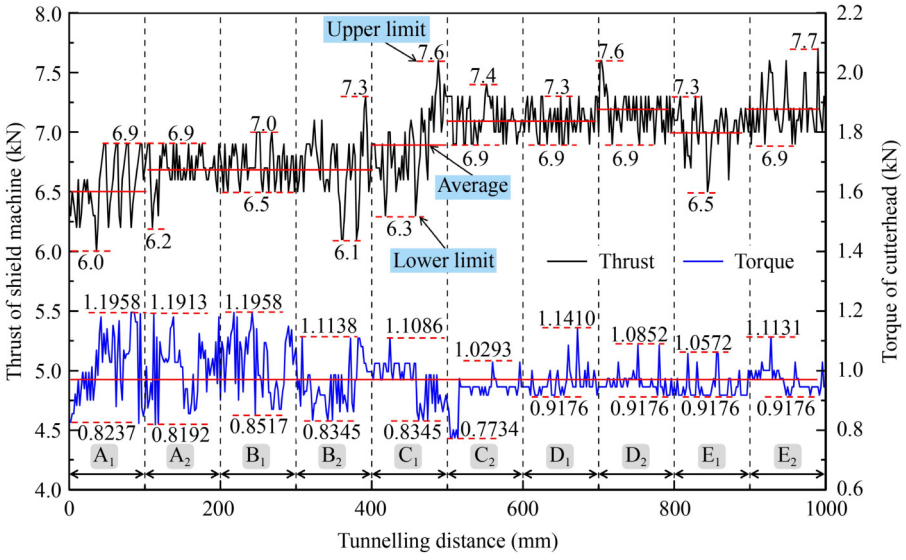



**Fig. 13** Thrust and torque curves of miniature EPB shield.

Soil pressure curves in the soil chamber of the miniature EPB shield are shown in Fig. 14. The pressure variation ranges for #1, #2, and #3 sensors are 5.0–11.1, 5.1–10.9, 5.1–11.9 kPa, with average values of 7.6, 7.9, and 7.9 kPa, respectively. The pressure fluctuation range (and average value) of each sensor in the soil chamber are close to each other, indicating the stable pressure in the soil chamber during the tunneling process. The proposed injection schemes ensure the stability of the excavation face and enhance the adaptability of shield machine excavation in composite strata with different sand–rock ratios.

Soil pressure curves in the soil chamber of the screw conveyor of the miniature EPB shield are shown in Fig. 15. The pressure variation ranges for #4, #5, and #6 sensors are 1.3–2.4, 0.9–2.0, and 0.6–1.7 kPa, with average values of 1.9, 1.4, and 1.2 kPa, respectively. The pressure fluctuation ranges of the sensors at different locations in the screw conveyor are different. The soil pressure of sensor #4, which is closest to the soil chamber, is the largest, followed by sensor #5, and sensor #6 is the smallest. When the shield machine is tunneling in a full-face sandy stratum, the soil pressure in the screw conveyor is generally lower than the average value.

The slump value of soil discharged from the screw conveyor was tested. It was found that the slump values of the soils from different sand–rock ratio strata were distributed within a reasonable range of 170–200 mm, and the flow plasticity of the soils was better. This experiment verifies the feasibility of the upgraded miniature EPB shield test system, which cannot only evaluate the flow plasticity of the conditioned soil but also assess the impact of soil conditioning on shield machine tunneling control.

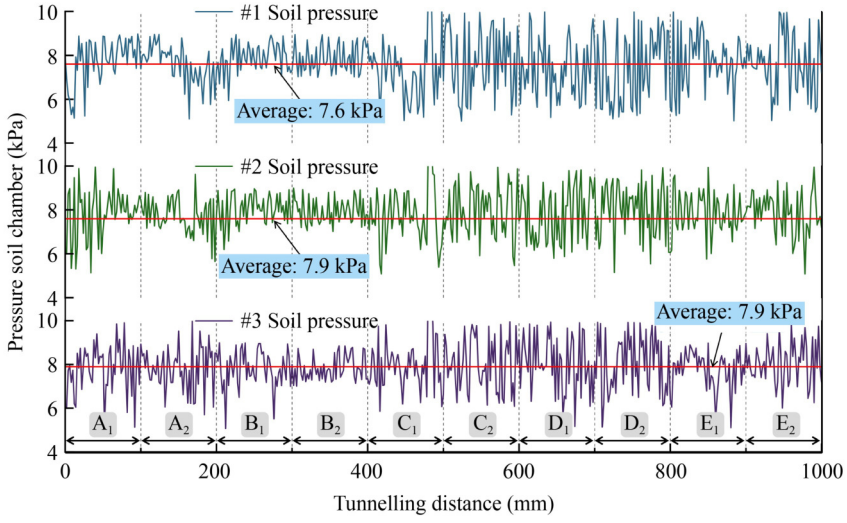



**Fig. 14** Soil pressure curves in the soil chamber of miniature EPB shield.

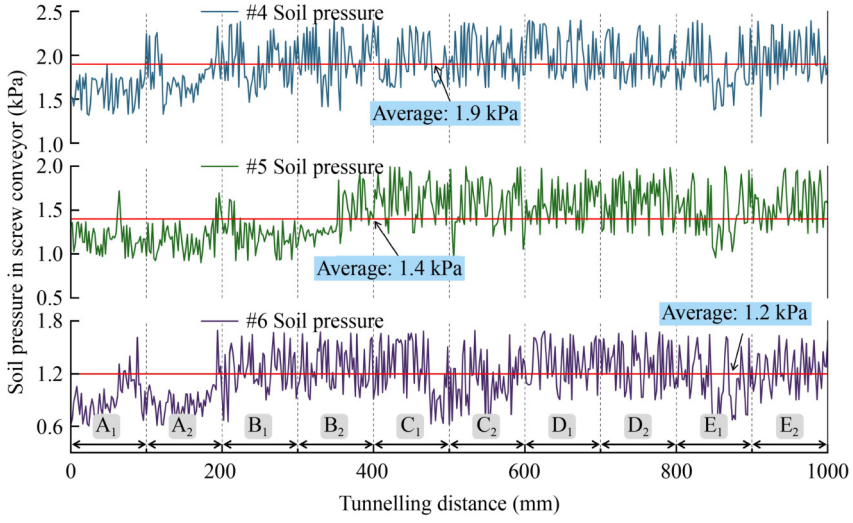



**Fig. 15** Soil pressure curves in screw conveyor of miniature EPB shield.

## 5 Field tests

### 5.1 Tunnel overview

The tunnels from the People's Park Station to Dinggong Road North Station on Nanchang Rail Transit Line 4 in China were constructed using the EPB shield excavation method. The buried depth of the tunnel ranges from 10.94 to 23.69 m, and the groundwater level is between 3.2 and 9.8 m below the surface.

Figure 16 shows the longitudinal engineering geology. The shield tunnel passes through strata that mainly consist of coarse sand, gravelly sand, round gravel, highly weathered argillaceous siltstone, and moderately weathered argillaceous siltstone, of which the combined percentage of gravelly sand and moderately weathered argillaceous siltstone reaches 80%. The EPB shield excavates from full-face sand ($\phi = \infty$) to full-face rock ($\phi = 0$) stratum. The tunneling distance in composite strata of gravelly sand and moderately weathered argillaceous sandstone accounts for about 50% of the total length of the tunnel. The detailed correspondences between sand–rock ratio and segment ring number are shown in Figs. 17–19 and will not be repeated here.

The high permeability of the gravelly sand increases the risk of water spewing from the screw conveyor during EPB shield tunneling. At the same time, the high cohesion of moderately weathered argillaceous siltstone also increases the risk of clogging the cutterhead and cutters. The composite ratio of the two strata on the excavation face is variable, and the performance of mixed soil in the soil chamber has a significant impact on the safety of shield tunneling.

### 5.2 Field test results

The soil conditioning schemes obtained in the laboratory were applied to the actual engineering environment. Ye et al. [17,46] proposed a method for calculating the foam consumption per ring of shield tunnel by considering the stratum looseness as well as the pressure of the soil chamber. Based on those studies, the conditioning material injection ratios (i.e., *FIR* and *BIR*) obtained from

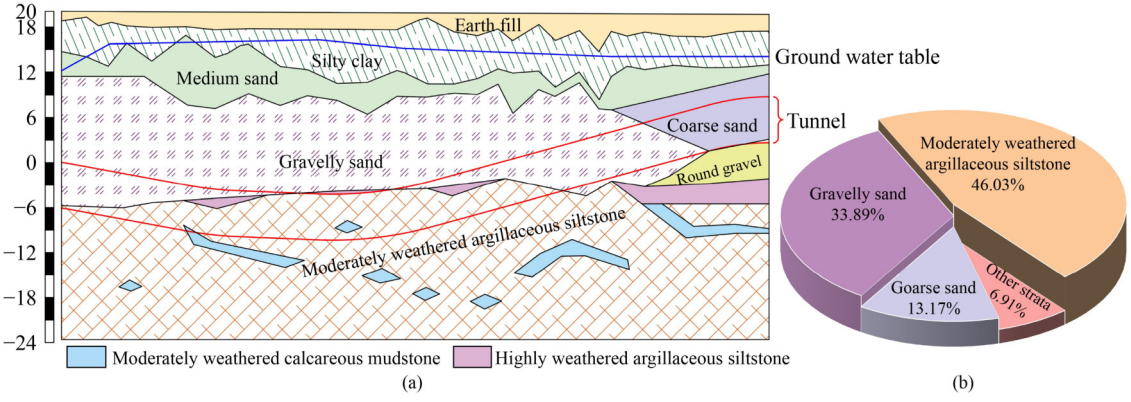



**Fig. 16** Engineering geology: (a) longitudinal geological profile; (b) proportion of strata within the range of shield tunneling.

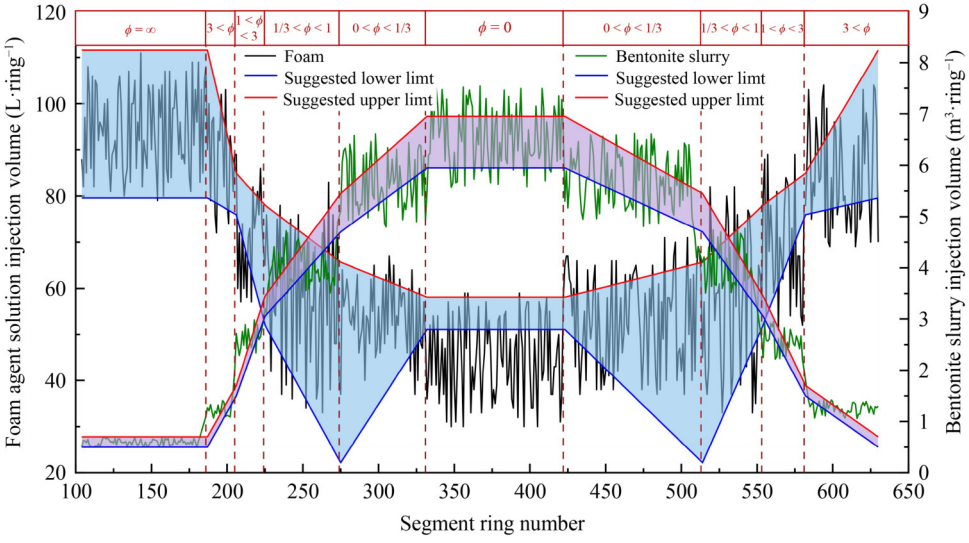



**Fig. 17** Injection volumes of foam agent solution and bentonite slurry in the actual engineering environment.

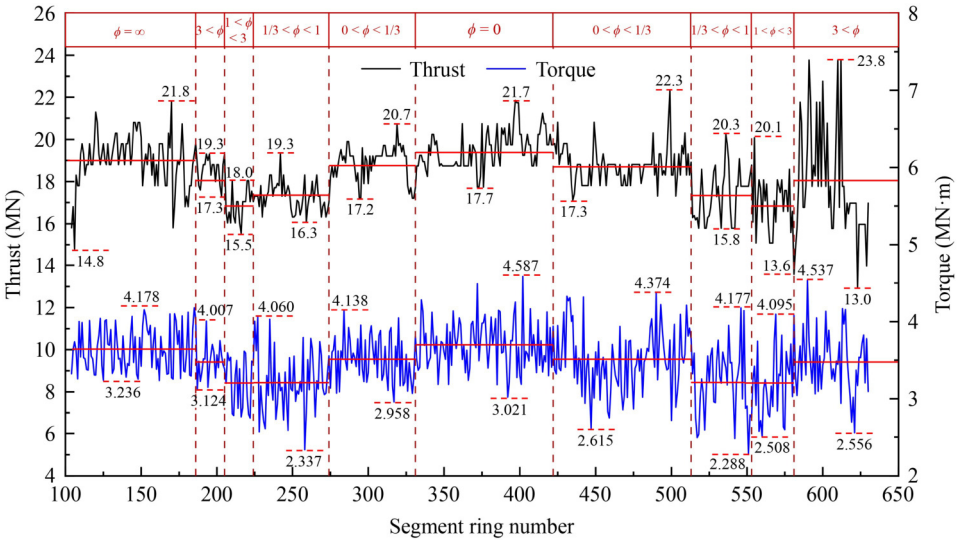



**Fig. 18** Thrust and torque of EPB shield in the actual engineering environment.

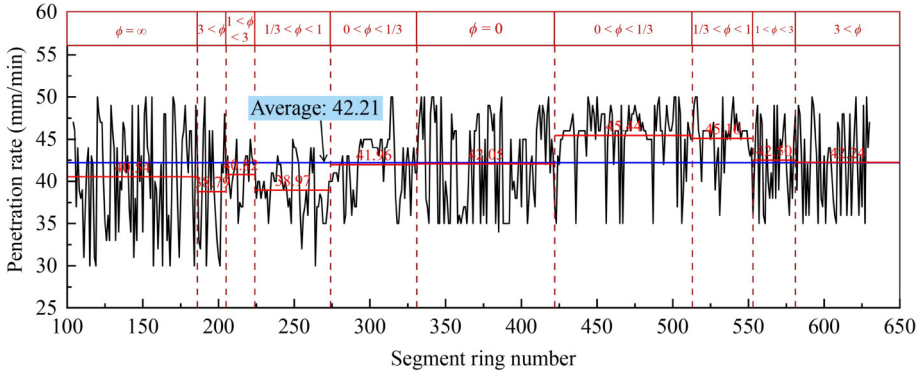



**Fig. 19** Penetration rate of EPB shield in the actual engineering environment.

the laboratory tests were converted to the injection volume per ring used in the engineering context. In the actual tunnel excavation, water was injected into the soil chamber to make the water content of the soil reach about 20%. The change curves of foam and bentonite slurry injection volume are shown in Fig. 17, in which the "suggested upper limit" and "suggested lower limit" are all converted from the laboratory test results given in Table 5.

As can be seen from the figure, the injected volume of foam and bentonite slurry in the actual engineering environment shows a fluctuating trend. The reason is mainly that the EPB shield is tunneling in water-rich strata, and the abundant groundwater leads to the water content of the soil in the soil chamber changing greatly. The injected volume of conditioning material has a sudden change every time the shield enters the next stratum. The amount of foam used in the sand stratum is larger than that in the rock stratum, with a difference of 49.4 L/ring, and the amount of bentonite slurry used in the rock stratum is larger than that in the sand stratum, with a difference of 5.96 L/ring. Comparing the actual and the recommended injection volume of conditioning material, it can be found that the two values are basically consistent, and the actual injection volume generally falls into the range of the recommended injection volume. The EPB shield did not show any water spewing from the screw conveyor or clogging the cutterhead and cutters during the entire tunneling process.

The change curves of thrust, torque, and penetration rate of the EPB shield in the actual engineering environment are shown in Figs. 18 and 19. The thrust range is 13.0–23.8 MN, which is less than the rated thrust of 37.0 MN, and the torque range is 2.228–4.587 MN·m, which is less than the torque results of Li et al. [18]. The average penetration rate is 42.21 mm/min, with a coefficient of variation of 12.12%. The relatively stable penetration rate in different strata indicates that the proposed soil conditioning schemes reduce the impact of strata changes on the penetration rate. There are no abnormal fluctuations in the thrust, torque, and penetration rate curves. It shows that the simultaneous use of foam and bentonite slurry for soil conditioning of water-rich composite strata improves the stability of shield machine tunneling, and the effect of soil conditioning is remarkable.

## 6 Conclusions

The changing sand–rock ratio on the excavation face leads to a greater risk of water spewing and clogging on the cutterhead, posing enormous challenges to soil conditioning. In this research, laboratory tests were performed on conditioned soil to determine the optimal injection ratios of conditioning materials for the composite strata with sand above and rock below. The soil conditioning effect and the characteristics of tunneling parameters in composite strata were investigated through model and field tests. The following conclusions can be drawn.

1) The 4:1 volume ratio of foam to bentonite slurry achieves better performance of the conditioned gravelly sand at a lower *TIR* (*TIR* < 10%). In the range of 1% ⩽ *TIR* ⩽ 10% and $\zeta$ = 4:1, both slump value and internal friction angle of the conditioned gravelly sand are approximately linearly correlated with *TIR*, and the permeability coefficient is significantly affected by the *TIR* at *TIR* < 3%.

2) The bentonite slurry has a significant improvement effect on the flow plasticity of crushed moderately weathered argillaceous siltstone. The influence of bentonite slurry on the slump value of conditioned soil is greater than that of foam. Keeping the water content and *TIR* constant, the slump value of conditioned soil decreases with the increase of *FIR*.

3) The optimal injection ratios for composite strata can be obtained by weighted summation according to the area ratio of different strata on the tunnel face based on the optimal injection ratios of conditioning materials for full-face sand and full-face rock.

4) A miniature EPB shield model test system was upgraded to model the soil pressure balance, conditioning material injection, and tunneling control. The model and field test results of thrust, torque, and soil pressure in the soil chamber and screw conveyor validate the effectiveness of the proposed soil conditioning schemes.

**Acknowledgements** This research was supported by the National Natural Science Foundation of China (Grant No. 52378414) and the Natural Science Basis Research Plan in Shaanxi Province of China (No. 2019JLP-23).

**Competing interests** The authors declare that they have no competing interests.

## References

1. Wang X, Zhang Y, Zhao W, Wang Z, Wang Z, Wang Y. Research on optimizing performance of new slurries for EPBS soil conditioning based on response surface method. Construction & Building Materials, 2023, 375: 130818
2. Wang X, Zhao W, Wang Z, Wang Z, Sun D, Tang X. Recycling the discharged soil from EPBS tunnels as a soil conditioner and its rheological behaviors. Journal of Cleaner Production, 2023, 418: 138224
3. Merritt A S, Mair R J. Mechanics of tunnelling machine screw conveyors: A theoretical model. Geotechnique, 2008, 58(2): 79–94
4. Peila D, Oggeri C, Vinai R. Screw conveyor device for laboratory tests on conditioned soil for EPB tunneling operations. Journal of Geotechnical and Geoenvironmental Engineering, 2007, 133(12): 1622–1625
5. Peila D, Martinelli D, Todaro C, Luciani A. Soil conditioning in EPB shield tunnelling—An overview of laboratory tests. Geomechanik und Tunnelbau, 2019, 12(5): 491–498
6. Wan Z, Li S, Yuan C, Zhao S, Wang M, Lu Q, Hou W. Soil conditioning for EPB shield tunneling in silty clay and weathered mudstone. International Journal of Geomechanics, 2021, 21(9): 06021020
7. Zumsteg R, Langmaack L. Mechanized tunneling in soft soils: Choice of excavation mode and application of soil-conditioning additives in glacial deposits. Engineering, 2017, 3(6): 863–870
8. Ali N, Bilal M, Khan A, Ali F, Iqbal H M. Effective exploitation of anionic, nonionic, and nanoparticle-stabilized surfactant foams for petroleum hydrocarbon contaminated soil remediation. Science of the Total Environment, 2020, 704: 135391
9. El Souwaissi N, Djeran-Maigre I, Boulange L, Trottin J L. Effects of the physical characteristics of foams on conditioned soil's flow behavior: A case study. Tunnelling and Underground Space Technology, 2023, 137: 105111
10. Kaptay G. On the equation of the maximum capillary pressure induced by solid particles to stabilize emulsions and foams and on the emulsion stability diagrams. Colloids and Surfaces. A: Physicochemical and Engineering Aspects, 2006, 282–283: 387–401
11. Ling F, Wang S, Hu Q, Huang S, Feng Z. Effect of bentonite slurry on the function of foam for changing the permeability characteristics of sand under high hydraulic gradients. Canadian Geotechnical Journal, 2022, 59(7): 1061–1070
12. Lu Y, Huang M, Huang P, Xu C, Wang Y, Hu Y. Soil conditioning for EPB shield tunneling in coastal silty clay strata: Laboratory research and field application. International Journal of Geomechanics, 2024, 24(2): 04023289
13. Yang Y, Wang G, Li H, Huang X. The new clay mud and its improvement effects of tunnels. Applied Clay Science, 2013, 79: 49–56
14. Avunduk E M R E, Copur H, Tolouei S, Tumac D, Balci C, Bilgin N, Shaterpour–Mamaghani A. Possibility of using torvane shear testing device for soil conditioning optimization. Tunnelling and Underground Space Technology, 2021, 107: 103665
15. Carigi A, Luciani A, Todaro C, Martinelli D, Peila D. Influence of conditioning on the behaviour of alluvial soils with cobbles. Tunnelling and Underground Space Technology, 2020, 96: 103225
16. Martinelli D, Todaro C, Luciani A, Peila D. Use of a large triaxial cell for testing conditioned soil for EPBS tunnelling. Tunnelling and Underground Space Technology, 2019, 94: 103126
17. Ye X, Wang S, Yang J, Sheng D, Xiao C. Soil conditioning for EPB shield tunneling in argillaceous siltstone with high content of clay minerals: Case study. International Journal of Geomechanics,

2017, 17(4): 05016002
18. Li S, Wan Z, Zhao S, Ma P, Wang M, Xiong B. Soil conditioning tests on sandy soil for earth pressure balance shield tunneling and field applications. Tunnelling and Underground Space Technology, 2022, 120: 104271
19. Xu Q, Zhang L, Zhu H, Gong Z, Liu J, Zhu Y. Laboratory tests on conditioning the sandy cobble soil for EPB shield tunnelling and its field application. Tunnelling and Underground Space Technology, 2020, 105: 103512
20. Hu Q, Wang S, Qu T, Xu T, Huang S, Wang H. Effect of hydraulic gradient on the permeability characteristics of foam-conditioned sand for mechanized tunnelling. Tunnelling and Underground Space Technology, 2020, 99: 103377
21. Huang S, Wang S, Xu C, Shi Y, Ye F. Effect of grain gradation on the permeability characteristics of coarse-grained soil conditioned with foam for EPB shield tunneling. KSCE Journal of Civil Engineering, 2019, 23(11): 4662–4674
22. Wang S, Huang S, Qiu T, Yang J, Zhong J, Hu Q. Analytical study of the permeability of a foam-conditioned soil. International Journal of Geomechanics, 2020, 20(8): 06020019
23. Wang S, Hu Q, Wang H, Thewes M, Ge L, Yang J, Liu P. Permeability characteristics of poorly graded sand conditioned with foam in different conditioning states. Journal of Testing and Evaluation, 2021, 49(5): 3620–3636
24. Huang Z, Wang C, Dong J, Zhou J, Yang J, Li Y. Conditioning experiment on sand and cobble soil for shield tunneling. Tunnelling and Underground Space Technology, 2019, 87: 187–194
25. Wang S, Ni Z, Qu T, Wang H, Pan Q. A novel index to evaluate the workability of conditioned coarse-grained soil for EPB shield tunnelling. Journal of Construction Engineering and Management, 2022, 148(6): 04022028
26. Peila D, Picchio A, Martinelli D, Negro E D. Laboratory tests on soil conditioning of clayey soil. Acta Geotechnica, 2016, 11(5): 1061–1074
27. Todaro C, Carigi A, Peila L, Martinelli D, Peila D. Soil conditioning tests of clay for EPB tunnelling. Underground Space, 2022, 7(4): 483–497
28. de Oliveira D G G, Thewes M, Diederichs M S. Clogging and flow assessment of cohesive soils for EPB tunnelling: Proposed laboratory tests for soil characterisation. Tunnelling and Underground Space Technology, 2019, 94: 103110
29. Vinai R, Oggeri C, Peila D. Soil conditioning of sand for EPB applications: A laboratory research. Tunnelling and Underground Space Technology, 2008, 23(3): 308–317
30. Hu W, Rostami J. A new method to quantify rheology of conditioned soil for application in EPB TBM tunneling. Tunnelling and Underground Space Technology, 2020, 96: 103192
31. Hu W, Rostami J. Evaluating rheology of conditioned soil using commercially available surfactants (foam) for simulation of material flow through EPB machine. Tunnelling and Underground Space Technology, 2021, 112: 103881
32. Lee H, Kwak J, Choi J, Hwang B, Choi H. A lab-scale experimental approach to evaluate rheological properties of foam-conditioned soil for EPB shield tunnelling. Tunnelling and Underground Space Technology, 2022, 128: 104667
33. ASTM. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System), ASTM D2488-17e1. West Conshohocken, PA: ASTM, 2020
34. Hollmann F S, Thewes M. Assessment method for clay clogging and disintegration of fines in mechanised tunnelling. Tunnelling and Underground Space Technology, 2013, 37: 96–106
35. Wu Y, Nazem A, Meng F, Mooney M A. Experimental study on the stability of foam-conditioned sand under pressure in the EPBM chamber. Tunnelling and Underground Space Technology, 2020, 106: 103590
36. Quebaud S, Sibai M, Henry J P. Use of chemical foam for improvements in drilling by earth-pressure balanced shields in granular soils. Tunnelling and Underground Space Technology, 1998, 13(2): 173–180
37. Sebastiani D, Vilardi G, Bavasso I, Di Palma L, Miliziano S. Classification of foam and foaming products for EPB mechanized tunnelling based on half-life time. Tunnelling and Underground Space Technology, 2019, 92: 103044
38. ASTM. Standard Test Method for Slump of Hydraulic-Cement Concrete, ASTM C143/C143M-20. West Conshohocken, PA: ASTM, 2020
39. ASTM. Standard Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions, ASTM D3080-04. West Conshohocken, PA: ASTM, 2012
40. GB/T 50123-2019. Standard for Geotechnical Testing Method. Beijing: Ministry of Water Resources of the People's Republic of China, 2019
41. Peila D, Oggeri C, Borio L. Using the slump test to assess the behavior of conditioned soil for EPB tunneling. Environmental & Engineering Geoscience, 2009, 15(3): 167–174
42. Budach C, Thewes M. Application ranges of EPB shields in coarse ground based on laboratory research. Tunnelling and Underground Space Technology, 2015, 50: 296–304
43. Yang Z, Yang X, Ding Y, Jiang Y, Qi W, Sun Z, Shao X. Characteristics of conditioned sand for EPB shield and its influence on cutterhead torque. Acta Geotechnica, 2022, 17(12): 5813–5828
44. Zhang K, Zhao X, Zhang Z. Influences of tunnelling parameters in tunnel boring machine on stress and displacement characteristics of surrounding rocks. Tunnelling and Underground Space Technology, 2023, 137: 105129
45. Wang H, Fu D. Theoretical and test studies on balance control of EPB shields. China Civil Engineering Journal, 2007, 40(5): 61–68, 110 (in Chinese)
46. Ye X, Wang S, Xiao C, Yang J, Zhou C. Soil conditioning test for soft upper and hard lower mixed stratum and its application. Modern Tunnelling Technology, 2015, 52(6): 147–153 (in Chinese)