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Green treatment technology of shield soil

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ABSTRACT

A large amount of shield soil will be discharged during the shield construction of the urban subways. The green treatment and recycling of the shield soil is one of the major concerns. Transporting and piling the shield soil is of high cost with large area occupation. At the same time, the shield soil containing various conditioning agents will cause environmental contamination in the piling process. In terms of the Earth Pressure Balance shield tunneling project of Xi'an Metro Line 10 in sandy strata, this study established a shield soil treatment system of separation of the shield soil into gravel, sand and clay for recycling, in order to increase the recycling rate of the shield soil and reduce piling. The results show that the shield soil treatment system operated by 8 workers can treat 800 m^3 shield soil per day, which can effectively increase the excavation speed by 1.5 m/d. The conversion rate of gravel and sand is about 55.4%, and the conversion rate of slurry cakes is about 29.6%. Gravel and sand can be used as raw materials for shotcrete and shield grouting, and dried slurry cakes can be used as backfill materials of top slabs or raw materials for sintered products. The shield soil treatment system effectively makes the shield soil harmless and recycled.

Keywords: shield soil treatment system, slurry-sand separation, slurry dewatering, resource recycling

1 INTRODUCTION

In China, the rapid growth of the population makes it difficult for the living space on the ground to meet people's needs. Especially in the past decade, the problem of ground traffic congestion in cities is very serious, which brings great inconvenience to people's travel. Therefore, the construction of underground traffic is increasing rapidly. As the main form of urban underground transportation, the subway has become an indispensable traffic tool for people. By 2021, the total length of subways in China is about 7.2×10^3 km, accounting for 78.3% of urban rail transits (China Association of Metros, 2022). The subway projects are mainly constructed by the shield method. A large amount of shield soil will be discharged during shield tunneling. Under the conditions of double-track shield construction, tunnel diameter of 6.5 m and soil loosening coefficient of 1.3, the amount of shield soil discharged per kilometer is about 4.3×10^4 m^3, and the total amount of shield soil during subway shield construction is about 3.1×10^8 m^3 by 2021. The shield soil has become the main component of municipal solid waste in China. Moreover, it is usually necessary to add conditioning agents such as bentonite slurry, foam or high polymer to the shield strata, in order to ensure construction safety and improve tunneling efficiency (Gharahbagh et al., 2014). However, the shield soil after being conditioned has high water content and usually contains various conditioning agents that are easy to cause environmental contamination (Cao et al., 2023; Zhang et al., 2022). A large amount of the shield soil without treatment are transported out for piling, which can easily cause the following problems.

(1) The shield soil with high water content is easy to leak during transportation, and is difficult to be transported out.

(2) A large amount of shield soil needs a large space for piling, which occupies a large area of land.

(3) The piled soil contains various conditioning agents, which easily pollute the surrounding environment.

(4) The shield soil usually has low strength and poor stability, and easily causes landslide disasters when piled.

The problems caused by piling the shield soil will greatly limit the sustainable development of cities. Therefore, it is necessary to conduct harmless treatment and recycling of the shield soil. The strata of shield tunneling in cities are mainly composed of sand and clay, with a small amount of gravel (Xie et al., 2022). Gravel, sand and clay, as necessities of building materials, are required in large quantities, and their costs are high in the construction. The green recycling of gravel, sand and clay from the shield soil can effectively reduce the cost of building materials and the accumulation of municipal solid waste. Developed countries such as the United States, France and Germany have advanced and complete soil treatment technologies and large-scale markets, and the resource conversion rate of the shield soil can reach more than 80% (Taboada et al., 2020). However, the subway constructions in China started relatively late. At present, the technologies of green treatment and recycling of the shield soil are backward in China, and has not formed a marketization scale (Zhao et al., 2010). The shield soil is still mainly piled, and its recycling rate is not high (Guo et al., 2020).

Therefore, this study built a shield soil treatment system for sandy strata in the construction site of the Earth Pressure Balance (EPB) shield project of Xi'an Metro Line 10. The shield soil treatment system has a slurry-sand separation system and a slurry dewatering system, which can separate the soil into gravel, sand and slurry cakes with low water content for recycling. The shield soil treatment system was applied in the construction site. This study will provide guidance and reference for the treatment of shield soil.

2 PROJECT PROFILE

The total length of the construction section from Xuefu Road Station to Weiyang Lake Station of Xi'an Metro Line 10 Project is about 4.85 km. The shield section of the project is about 3.76 km, accounting for 77.5% of the total construction length. The shield section is mainly composed of medium sand, with fine sand, coarse sand or mixed areas of fine sand and silty clay in some areas. The typical geological profile of the shield section is shown in Figure 1. During shield construction, two Earth Pressure Balance shield machines with a diameter of 6.47 m were used for double-track tunneling. The total tunneling length is about 7.52 km, and the shield soil production is about 2.43×10^5 m^3.

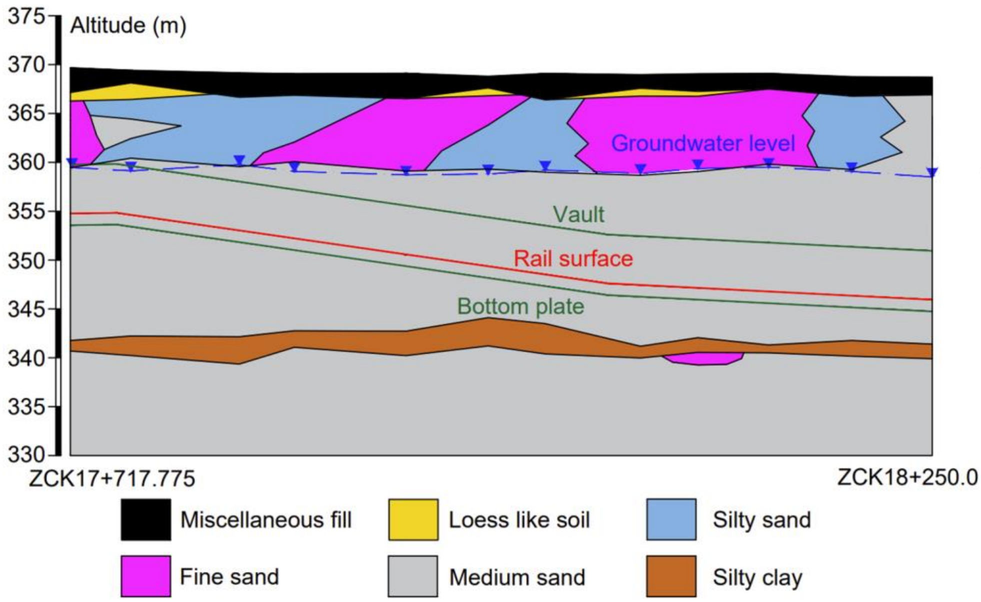

Figure 1. *Typical geological profile of the shield section (Wu et al., 2022)*

3 SHIELD SOIL TREATMENT SYSTEM

In this study, a shield soil treatment system suitable for sandy strata was established in a closed steel structure plant, as shown in Figure 2. The treatment system includes slurry-sand separation system and slurry dewatering system, as shown in Figure 3. The treatment system can separate the shield soil into recyclable gravel, sand and clay. It can effectively solve engineering problems such as low recycling rate of shield soil and environmental contamination, and realize green treatment and resource utilization of shield soil.

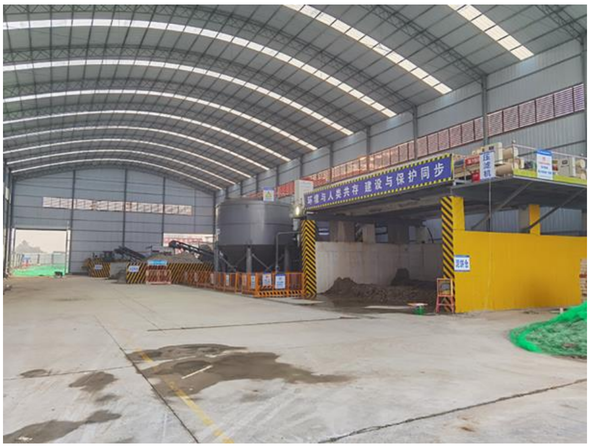

Figure 2. *Shield soil treatment system runs in a closed steel structure plant*

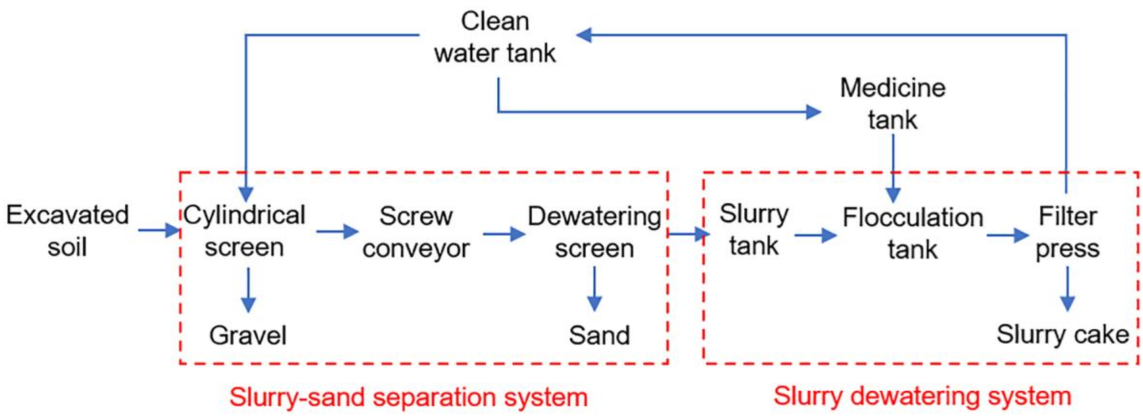

Figure 3. *Shield soil treatment system*

3.1 Slurry-sand separation system

The slurry-sand separation system is mainly composed of a cylindrical screen, screw conveyor and dewatering screen. After being treated by the slurry-sand separation system, the shield soil can be separated into gravel, sand, and slurry with bentonite and foam agent dissolved. The gravel and sand can be recycled, and the slurry flows into the slurry dewatering system for further treatment.

3.1.1 Preliminary screening with cylindrical screen

Cylindrical screen placed at an angle in the horizontal direction is used to separate soil particles of different sizes. When the cylinder screen rotates, soils are input from one end of the cylinder screen. After screening, the coarse soil particles are output from the other end of the cylinder screen, and the fine soil particles passing through the screen mesh are output from the lower part of the cylinder screen.

During the construction, the shield soil is input into the cylindrical screen with an excavator, as shown in Figure 4 (left). The cylindrical screen has two layers of screens. The first layer is a coarse screen with a hole diameter of 10 mm. The second layer is a fine screen with a hole diameter of 5 mm. When the cylindrical screen rotates, it can drive the soil to overturn and roll. The gravel with particle size greater than 5 mm in the soil are left on the screen and output from the end of the cylindrical screen. The sand and slurry passing through the screen in the soil are input into the screw conveyor from the lower part of the cylindrical screen, as shown in Figure 4 (right). In addition, the soil in the cylindrical sieve is dispersed by jet water to avoid particle agglomeration.

Figure 4. *Excavator (left). Cylindrical screen (right)*

3.1.2 Screw conveyor for sand washing

Screw conveyor can wash and transport sand by stirring its spiral blades, as shown in Figure 5 (left). Before the spiral blades stir the mixture of sand and slurry, defoamer is added to the mixture to neutralize the foam agent, so as to prevent foam generated by the foam agent from affecting sand washing. During stirring the mixture with the spiral blades, the large specific gravity of sand particles and the large friction resistance between sand particles and the screw conveyor make it difficult for sand particles to spiral with the spiral blades, but sand particles are pushed to the output end by the spiral blades. The slurry in the mixture has strong flowability and can flow significantly with the rotating spiral blades, so as to preliminarily separate the slurry and sand particles. Sand particles roll in the process of being pushed by the spiral blades. Friction occurs between rolling sand particles and between rolling sand particles and the screw conveyor, which reduces impurities such as bentonite and foam agent on the surface of sand particles. In addition, the flowing slurry can wash the surface of sand particles to further remove impurities. The sand and slurry treated by the screw conveyor are input into the dewatering screen.

3.1.3 Dewatering screen for sand dewatering

Dewatering screen is used to dewater sand, and transform it into recyclable resources, as shown in Figure 5 (right). The dewatering screen has a vibrating screen and four high-pressure swirlers. The vibrating screen can screen out coarse sand in the soil. High-pressure swirlers can screen out medium-fine sand in the soil.

Figure 5. *Screw conveyor (left). Dewater screen (right)*

The vibrating screen is mainly composed of a motor, vibrator, screen box, supporting device and transmission device. The motor uses belts to drive two symmetrically installed vibrators to run synchronously and reversely. The components of centrifugal forces in the vertical vibration direction generated by the rotating eccentric blocks in the two vibrators are offset each other, and the components of centrifugal forces in the vibration direction are superposed to make the screen box move in a reciprocating straight line along the vibration direction. The screen box has two layers of polyurethane screen. The first layer is a coarse screen with a hole diameter of 2 mm, and gravel particles with a particle size larger than 2 mm can be left on the coarse screen. The second layer is a fine screen with a hole diameter of 0.5 mm, and coarse sand with a particle size larger than 0.5 mm can be left on the fine screen. The sand and slurry entering the vibrating screen vibrate strongly on the screen. The coarse sand with particle size larger than 0.5 mm can be left on the screen, while the medium-fine sand and slurry passing through the screen mesh flow into the water tank under the vibrating screen. The mixture of the medium-fine sand and slurry in the water tank is pumped into the high-pressure swirlers with a mortar pump to separate the medium-fine sand and slurry.

The high-pressure swirlers are used to separate the medium-fine sand and slurry based on the principle of centrifugal sedimentation, as shown in Figure 6. The mixture of medium-fine sand and slurry flows into the swirlers at a certain pressure from the soil inlet, and is forced to rotate along the wall of the swirlers to form an external swirl. The medium-fine sand particles subjected to greater centrifugal forces in the mixture overcome the resistance of the surrounding liquid and move towards the wall of the swirlers. At the same time, the medium-fine sand particles move downward along the wall spirally and are discharged from the sand outlet under the action of their own gravity. The fine particles with particle size less than 0.075 mm and most of the water subjected to smaller centrifugal forces do not rotate near the wall of the swirlers, but flow to the axis of the swirlers under the radial pressure difference. As the diameter at the bottom of the swirlers gradually decreases, the liquid pressure gradually increases. However, the overflow port is a low-pressure area. Under the axial pressure difference, the slurry formed by the fine particles and water moves upward along the axial direction to form an internal swirl, and is discharged from the overflow port. The slurry discharged from the overflow port flows into the sewage tanks and will be dewatered.

Figure 6. *High-pressure swirler*

3.2 Slurry dewatering system

The slurry dewatering system includes flocculation dewatering and filter press dewatering, which is mainly composed of two slurry pumps, two flocculation tanks, two medicine tanks and two filter presses. The volume of the flocculation tank and medicine tank is 100 m^3. The slurry after flocculation dewatering can form slurry flocs. The slurry flocs can form slurry cakes with low water content after filter press dewatering. The clean water produced in the dewatering process can be recycled.

3.2.1 Flocculation dewatering

The slurry in the slurry tanks is pumped into the flocculation tanks by the slurry pump for flocculation. Polymer flocculant solution is prepared in the medicine tanks. After standing for 24h, the flocculant solution is injected into the slurry in the flocculation tanks. After sufficient standing, the slurry flocs are formed at the bottom of the flocculation tanks, and the upper part of the slurry flocs is clear water separated from the slurry, so as to complete the flocculation dewatering. The clear water separated from the slurry is pumped into the clear water tanks by a water pump for sand washing or preparation of the flocculant solution. The slurry tanks, clean water tanks and flocculation tanks are shown in Figure 7 (left), and the medicine tanks are shown in Figure 7 (right). The slurry flocs are pumped into the filter presses by the slurry pump for the filter press dewatering.

Figure 7. *Slurry tank, clean water tank and flocculation tank (left). Medicine tank (right)*

3.2.2 Filter press dewatering

In this study, the programmable automatic chamber filter presses are used for the filter press dewatering of the slurry flocs. The programmable automatic chamber filter press is mainly composed of filter plates, frames, an automatic pneumatic closing system, a measuring plate suspension system, a filter plate vibration system, an air compression device and a high-pressure washing device. The main parameters of the chamber filter presses are shown in Table 1.

Table 1. *The main parameters of the programmable automatic chamber filter press*

Model	**Filter area (m^2)**	**Volume of filter rooms (m^3)**	**Number of filter rooms**	**Filtration pressure (MPa)**	**Motor power (kW)**	**Overall dimensions (m)**
X(AM)Z500/1500-30U	500	7.478	123	0.5	5.5	11.46 × 1.9 ×1.92

The filter press dewatering of the slurry flocs is carried out in two steps. Firstly, the slurry flocs are pumped into the filter rooms by the slurry pump. The slurry flocs are dewatered under the pump pressure, and the water flows into the collection device through the filter clothes on both sides of the filter rooms. Secondly, the slurry flocs in the filter rooms are pressed by the plate frames of the chamber filter presses, and the slurry flocs are dewatered to form slurry cakes with low water content. During the operation of the slurry dewatering system, two chamber filter presses work on the slurry cake bin at the same time and press the slurry flocs into slurry cakes with low water content. The slurry cakes fall into the slurry cake bin, as shown in Figure 8. The clean water pressed from the slurry flocs flows back to the clean water tanks for recycling.

Figure 8. *Filter press dewatering of the slurry*

3.3 Characteristics of the treatment system

The shield soil treatment system runs in a fully enclosed plant, and has high mechanization and fast soil treatment speed. The water discharged in the treatment process can be recycled, which can effectively save water resources and reduce environmental contamination. The treatment system is mainly applicable to the green treatment of the shield soil in sandy strata. It can separate the shield soil into sand, soil and other raw materials that can be recycled directly, and effectively solve the problem of piling the shield soil. However, the treatment system is not effective for clay strata.

4 TREATMENT EFFICIENCY AND UTILIZATION OF SOIL

The construction plan of the project requires 13 months to complete the shield tunneling. The shield soil production is about 2.43×10^5 m^3 in the shield section. Therefore, about 623 m^3 of shield soil are discharged every day and need to be treated. According to the data statistics of the construction site, the shield soil treatment system can effectively improve the soil treatment speed and the shield tunneling speed. The soil treatment speed is about 800 m^3/d, and only 8 workers are needed to maintain the effective operation of the whole treatment system, which can effectively increase the excavation speed by 1.5 m/d.

In the shield soil treatment system, the daily output of sand and gravel is about 443 m^3, and the conversion rate is about 55.4%. The slurry dewatering system significantly reduces the water content of slurry, and forms slurry cakes with a water content of about 40%. The daily output of slurry cakes is about 237 m^3. The slurry cakes have low water content and small volume, which is convenient for transportation and recycling. The gravel and sand discharged in the slurry-sand separation system can be used as raw materials for shotcrete in foundation pit excavation or shield grouting. The clay slurry cakes formed in the slurry dewatering system can be used as backfill materials of top slabs after being dried, or be transported to the surrounding brick factories and ceramic factories by the transportation companies as the main raw materials of sintered products. The clean water discharged in the slurry dewatering system can be recycled to the clean water tanks for sand washing or preparation of flocculant solution, and form a recycling process of water resources. According to Earth Pressure Balance shield tunneling project of Xi'an Metro Line 10, it is estimated that the shield soil treatment system can save shield soil transportation cost of 250000 ¥/km and water cost of 15000 ¥/km.

5 CONCLUSIONS

In the study, the green treatment system was developed to separate the shield soil into recyclable resources. The conclusions of the study are as follows.

(1) The shield soil treatment system was designed and established including slurry-sand separation system and slurry dewatering system. The slurry-sand separation system separates the shield soil into gravel, sand and slurry. The slurry can form slurry cakes with low water content after being treated by the slurry dewatering system.

(2) The shield soil treatment system has high treatment efficiency and low pollution. The treatment speed of the shield soil treatment system operated by 8 workers is 800 m^3/d, which can effectively increase the excavation speed by 1.5 m/d. The daily output of sand and gravel is about 443 m^3, and the conversion rate is about 55.4%. The daily output of slurry cakes is about 237 m^3, and the conversion rate is about 29.6%. The clean water discharged in the slurry dewatering system can be recycled to save water resources and reduce water pollution.

(3) The shield soil can be effectively recycled after treatment. The separated sand and gravel can be used as raw materials for shotcrete in foundation pit excavation or shield grouting. The slurry cakes formed by the chamber filter presses can be used as backfill materials of top slabs or raw materials of sintered products.

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