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Effects of structural characteristics of screw conveyor on spewing during EPB shield tunnelling

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Abstract. During EPB shield tunnelling, construction speed and safety are severely affected by spewing. In this study, a theoretical seepage model is established to capture of the effects of screw conveyor geometry and turbulent flow on spewing. Experimental test results are used to verify the proposed theoretical seepage model. It is found that the seepage is greatly affected by the length of screw conveyor and soil permeability. The proposed model can increase the screw conveyor length and reduce soil discharge sections simultaneously, the permeability of treated muck thus decreases by one order of magnitude. By using the proposed theoretical seepage model, the criterion of critical soil permeability used to identify spewing is proposed. When the water head applied at tunnel face reaches 40 m and 50 m, the critical permeability coefficients of treated muck should be less than 10^{-5} m/s and 10^{-6} m/s to avoid spewing. For a given permeability coefficient of soil, the water flow rate is overestimated if structural characteristics of screw conveyor is not considered. Consequently, the occurrence of spewing is greatly overestimated, which increases construction cost substantially.

Keywords: critical permeability coefficient; EPB shield tunnelling; screw conveyor; spewing

1. Introduction

Earth pressure balance shielding is widely used in practice since it can ensure construction quality and effectively alleviate the adverse effects on nearby infrastructures (Shi *et al.* 2022, 2023, Lu *et al.* 2019, 2020).

Compared with the traditional shield machine, a waterproof plate was installed in the middle of the shield to separate tunnel face and shield tunnel. Thus, sealed soil cabin was formed between the waterproof plate and the tunnel surface. The cutterhead worked in the soil cabin, and the screw conveyor was installed via the waterproof plate. During advancement of tunnel construction, the sealed soil cabin and screw conveyor were filled with muck. The water pressure applied at the tunnel face was balanced by the reaction force provided by muck soil. However, it was not uncommon to encounter spewing at the outlet of the screw conveyor when tunnel constructed in the sand and gravel stratum with large permeability (e.g., Prendes-Gero *et al.* 2013, Zhang *et al.* 2015). Consequently, excessive ground movements due to tunnel construction may be induced (e.g., Prendes-Gero *et al.* 2013, Shao *et al.* 2022, Xue *et al.* 2019, Zhang *et al.* 2015, Zhu *et al.* 2004, Zheng *et al.* 2015, Zhao *et al.* 2020), which may cause additional deformation and stress in adjacent infrastructures.

Currently, many research attentions were paid to spewing mechanisms. By conducting experimental tests, Zhu *et al.* (2004) explored the mechanism of spewing in screw conveyor. It was found that the permeability coefficient of soil was the most important parameter affecting the spewing. Merrit and Mair (2006) established the linear relationship between the total pressure in the screw conveyor and water pressure. Moreover, Merrit and Mair (2008) investigated the effects of soil particle size and properties on distribution of water/soil pressures and torque in the screw conveyor. Based on computational fluid dynamics, Kaveh *et al.* (2014) simulated the flow characteristics of soil in screw conveyor. Zheng *et al.* (2015) found that turbulence flow occurred in the tunnel shield when the water head at the tunnel face was high and permeability coefficient of muck was large. By considering additional thrust applied to the screw conveyor, Zhao *et al.* (2015) established early warning criterion of spewing based on the critical spewing conditions.

Since excessive ground movements were induced by spewing, a series of countermeasures were developed to prevent and control spewing. Among all the countermeasures, reductions of soil permeability and hydraulic gradient were the most popular way to suppress spewing (e.g., Peila *et al.* 2007, Christoph Budach *et al.* 2015, Zhou *et al.* 2020, Wang *et al.* 2020, Wang *et al.* 2020, Jiang *et al.* 2007, Mi 2020). Moreover, redesign of the screw conveyor was another effective way to avoid spewing. Jiang (2007) developed a double screw conveyor to ensure the stability of tunnel face. By using the developed conveyor, the spewing was prevented even under high water conditions. Based on numerical simulation Shangguan *et al.* (2010) presented the relationship between the increment of earth pressure and the angular velocity of screw conveyor, to reduce the occurrence of spewing, it is necessary to control the speed of the screw conveyor. Mi

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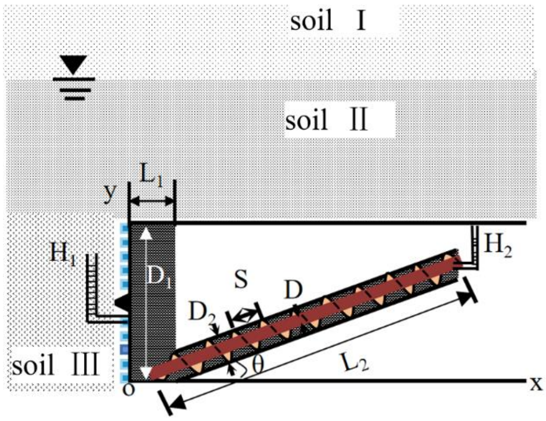


Fig. 1 Seepage model of shield pressure chamber-screw conveyor

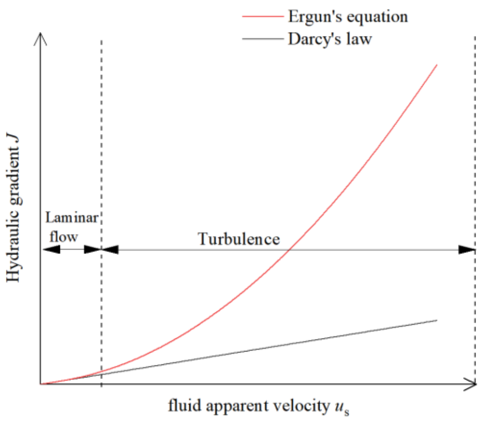


Fig. 2 Comparison between Darcy's law and Ergun's equation

(2020) developed a new type of screw conveyor with variable pitch to form soil plug section inside the conveyor, which could effectively control the occurrence of spewing. Based on the theory of CFD, Cui *et al.* (2022) think that screw pitch of 600mm can reduce the spewing accidents.

Previous studies mainly focused on spewing mechanisms and countermeasures used to avoid spewing. Several types of new screw conveyors were developed to prevent spewing. However, the mechanism that the geometric characteristics of the screw conveyor affect the spewing is still unclear. Based on the turbulence theory, the effects of screw conveyor geometry, water pressure at tunnel face, soil permeability on seepage mechanism of soil in the tunnel chamber and the screw conveyor were investigated in this study. Moreover, a theoretical model was proposed to evaluate spewing during EPB shield tunnelling.

2. Establishment of a theoretical seepage model of shield pressure chamber-screw conveyor

Fig. 1 shows a schematic diagram of seepage model of shield pressure chamber-screw conveyor. The water head at the tunnel face and screw conveyor were H_1 and H_2, respectively. The assumptions made for this seepage model are listed as follows (e.g., Zhu *et al.* 2007, Zheng *et al.* 2015):

1) The whole pressure chamber and screw conveyor are fully filled by muck soil. The soil is assumed as an isotropic and saturated material.

2) During the seepage of ground water, the local water head loss due to the inner wall and spiral blades of the screw conveyor is ignored.

3) During the process of ground water seepage, the groundwater and soil are assumed to be incompressible. In other words, soil deformations induced by seepage is not considered.

4) During the entire seepage process, the speed of soil discharge is not considered.

In general, laminar flow dominates ground water seepage in the pressure chamber-screw conveyor (Zheng *et al.* 2015). However, the turbulence flow cannot be avoided when there is spewing. Because of high seepage velocity and large size of soil particle, water flow may change from laminar flow to turbulent flow. A parameter, called Reynolds number (Re), is used to differentiate the laminar and turbulent flows. When the value of Reynolds number is less than 10, the water seepage can be classified as laminar flow. Otherwise, it is a turbulence flow. The Reynolds number (Re) is calculated by Eq. (1)

$$Re = u_s \frac{d_p}{v_f} \tag{1}$$

where u_s is the superficial velocity of fluid, d_p is the average particle size of soil, v_f is the kinematic viscosity of fluid. For groundwater, the value of v_f is 1.002×10^{-6} m^2/s at the temperature below 20 degrees Celsius.

In general, the water flow in the porous material cannot be considered as laminar flow when the Reynolds number is higher than 10. Currently, the water flow can be considered to transmit from laminar flow to turbulent flow. The Ergun formula is used to describe this flow state, as shown in Eq. (2)

$$J = 150\frac{(1-n)^2 \cdot v_f}{d_p^2 \cdot g \cdot n^3} u_s + 1.75\frac{(1-n)}{d_p \cdot g \cdot n^3} u_s^2 \tag{2}$$

where J is the hydraulic gradient, n is the material porosity, g is the gravitational acceleration. The first item of the formula is derived based on Darcy formula and Kozeny-Carman (KC) equation. Thus, this formula can reasonably describe the laminar flow at low flow velocity. As an increase in the flow velocity, the second item dominates the hydraulic gradient (J). Since the hydraulic gradient is proportional to the square of the flow velocity, the equation (2) can well capture turbulent flow, as shown in Fig. 2.

Actually, seepage in the soil chamber of tunnel shield is a typical three-dimensional problem. Because of complex boundary conditions, it is difficult to derive analytical solutions. Thus, numerical modeling is used to analyze the flow properties in the soil chamber of tunnel shield. The flow along the screw conveyor is simplified as one-dimensional flow in pipes. Since the flow velocity of water in the screw conveyor is greater than that in the pressure

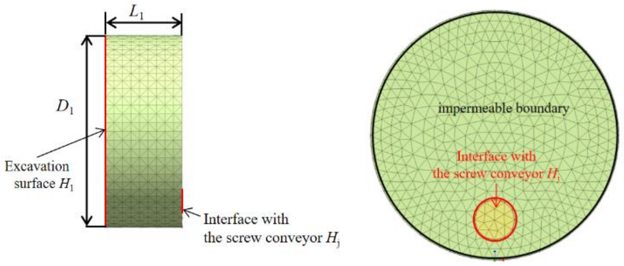


Fig. 3 Finite element model diagram of pressure chamberr

Table 1 Parameters of tunnel shield and muck soil

Pressure chamber	Muck soil		
Excavation surface diameter D_1 (m)	Length L_1 (m)	Water head of excavation face H_1 (m)	Permeability coefficient of sand, K (m/s)
6.2	2.6	20~26.2	1×10^{-5}

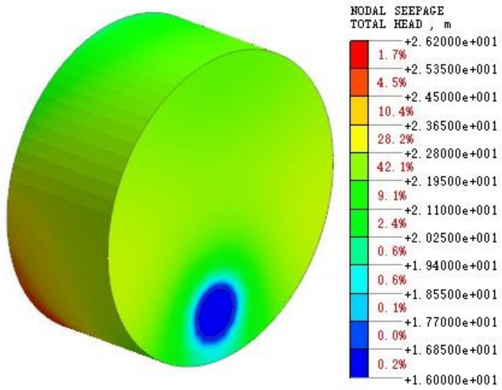
chamber, turbulent flow is more likely to occur in the screw conveyor. To simplify the complex seepage problems, the laminar flow is assumed in the pressure chamber, while Ergun formula is used to analyze water flow in the screw conveyor (Zheng *et al.* 2015). Consequently, two theoretical models are established for the screw conveyor and the shield pressure chamber, respectively. Using the same boundary conditions at the interface between the pressure chamber and screw conveyor, the flow velocity can be obtained (e.g., Zhu *et al.* 2007, Zheng *et al*. 2015, Zhao *et al.* 2020).

2.1 The theoretical seepage model in the pressure chamber of shield

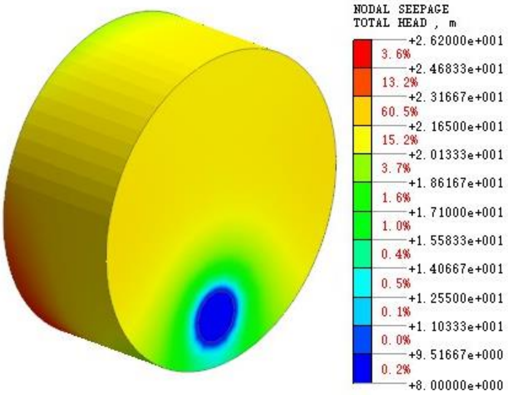
Firstly, calculate the stable seepage field inside the pressure chamber under different outlet water heads. Table 1 summarizes the parameters of tunnel shield and muck soil used in this study. The tunnel is constructed in sandy layer with a permeability coefficient of 1×10^{-5} m/s. By using the commercial software Midas GTS NX, the seepage model of pressure chamber of shield was established, as shown in Fig. 3. In total, this three-dimensional mesh consisted of 21016 tetrahedral elements. An inlet boundary with water head of 20~26.2 m was applied at the tunnel face. An outlet boundary was applied at the interface at the screw conveyor. Impermeable conditions were applied in other boundaries.

By assuming the water head at the interface of the screw conveyor (H_j) as 0~20 m, the water head distribution within the pressure chamber is shown in Fig. 4. It is clearly shown that the water head surrounding screw conveyor is closed to the assumed head a. The far away from the screw conveyor, the high the water head. Fig. 5 shows the relationship between the outlet flow rate and the outlet boundary head.

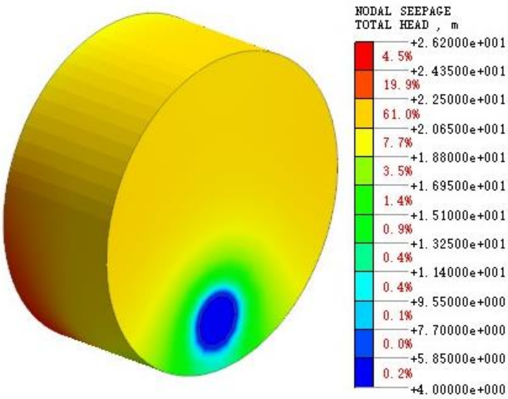
As an increase in the outlet head (H_j), the flow rate of water within pressure chamber decreases linearly. Fig. 5 shows the stable seepage outlet flow rate of the pressure



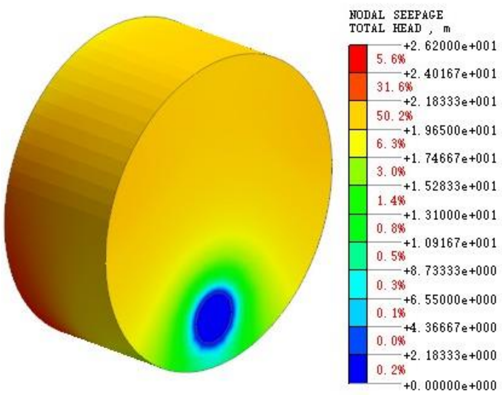
(a) H_j=16 m



(b) H_j=8 m



(c) H_j=4 m



(d) H_j=0 m

Fig. 4 Head distribution of pressure chamber

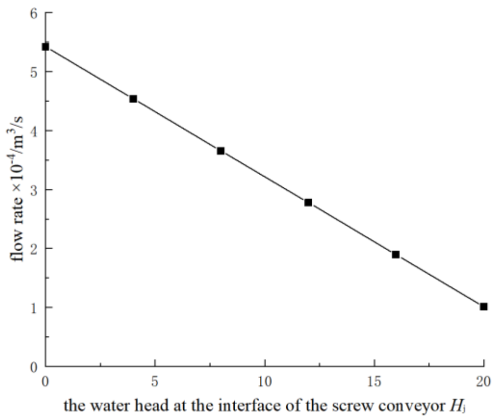
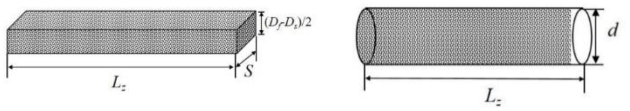


Fig. 5 Relationship between flow rate and H_j



(a) Expansion model of cuboid (b) Expansion model of cylinder

Fig. 6 Stretched diagram along the soil discharge of screw conveyor

chamber under different outlet heads. It can be seen that a linear relationship between outlet flow rate and water head is observed. Because the inlet boundary of the screw conveyor is equal to the outlet boundary of the pressure chamber, the actual flow rate inside the entire shield machine and the water head at that location can be determined.

2.2 Establishment of theoretical seepage model in the screw conveyor

Because of the special structural characteristics of the screw conveyor, soil is discharged in a spiral line. Thus, the seepage path should be the same as that of soil discharge. In this study, the spiral blade is expanded along the path of soil discharge to obtain a simplified model of soil discharge, as shown in Fig. 6. By ignoring head loss at the corners of the cuboid, the cuboid model can be equivalent to a cylinder. The diameter of the cylinder is the hydraulic diameter of the cuboid, as calculated by Eq. (3)

$$d=\frac{2A}{\chi} \tag{3}$$

where d is the hydraulic diameter, A is cross-section area of the cuboid, $A=(D_f-D_2)S/2$. D_f is the inner diameter of screw conveyor, D_2 is the diameter of shaft rod of screw conveyor, and S is the length of screw conveyor, $\chi=D_f-D_2+2S$ is the wetted perimeter of cuboid.

By simplifying the screw conveyor as a cylinder, the seepage can be considered as one-dimensional flow. The water head at the outlet of the screw conveyor is expressed as $L_2 sin\theta+Dcos\theta/2+H_o$, where H_o is the pressure head at the outlet of the screw conveyor. By substituting water head at the outlet of the screw conveyor into Eq. (2) and integrating both sides along the expansion model of cylinder, the seepage equation of the equivalent cuboid is obtained as follows

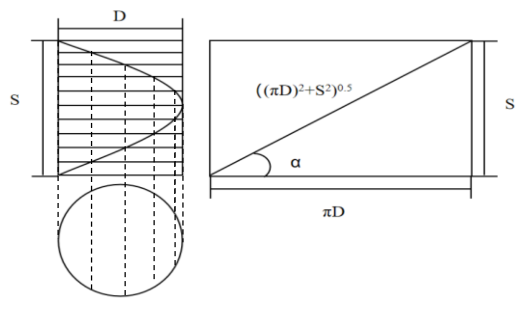


Fig. 7 Schematic diagram of spiral expansion

$$\int_{L_2 sin\theta+\frac{D}{2}cos\theta+H_o}^{H_j} dH = \int_0^{L_z}\left[150\frac{(1-n)^2\cdot v_f}{d_p^2\cdot g\cdot n^3}u_s+1.75\frac{(1-n)}{d_p\cdot g\cdot n^3}u_s^2\right]dl \tag{4}$$

where θ is the inclination angle of screw conveyor; L_z is the length of expanded screw conveyor, the expansion length L_z can be calculated by spiral line theory, as shown in Fig. 7.

The cylinder in the Fig. 7 represents the diameter of the screw conveyor, and the spiral line represents the blade, which is the actual path of soil discharge. Therefore, the cylinder can be expanded along any circumference to obtain a rectangle. The diagonal length of the rectangle is the actual extent of the spiral line after unfolding. The length is the circumference of the cylindrical shaft, and the width is the length of a screw pitch. Thus, L_z can be calculated as $L_z=(L_2/S)\cdot\sqrt{(\pi D)^2+S^2}$, where L_2 is the actual length of the screw conveyor.

The seepage flow in the cylinder model can be calculated by Eq. (5).

$$Q=\frac{\pi}{4}d^2u_s \tag{5}$$

Assuming that the water head H_j at the intersection of screw conveyor and pressure chamber is known, substitute Eq. (5) in to Eq. (4)

$$H_j=L_2 sin\theta+H_o+\frac{D}{2}cos\theta+(\frac{L_2}{S})\left[(\pi D)^2+S^2\right]^{0.5}\cdot\left[600\frac{(1-n)^2\cdot v_f\cdot Q}{d_p^2\cdot g\cdot n^3\cdot\pi d^2}+28\frac{(1-n)\cdot Q^2}{d_p\cdot g\cdot n^3\cdot\pi^2 d^4}\right] \tag{6}$$

The above equation is a quadratic equation about Q, and the expression for Q can be obtained.

$$\begin{aligned}(\frac{L_2}{S})\left[(\pi D)^2+S^2\right]^{0.5}\cdot 28\frac{(1-n)}{d_p\cdot g\cdot n^3\cdot\pi^2 d^4}&=a\\(\frac{L_2}{S})\left[(\pi D)^2+S^2\right]^{0.5}\cdot 600\frac{(1-n)^2\cdot v_f}{d_p^2\cdot g\cdot n^3\cdot\pi d^2}&=b\\L_2 sin\theta+H_o+\frac{D}{2}cos\theta-H_j&=c\end{aligned} \tag{7}$$

The flow discharge Q is obtained as shown in Eq. (8)

Table 2 Model geometry and soil permeability coefficient

Screw conveyor				
Inner diameter D（mm）	Shaft rod D_2（mm）	Actual length L_2（mm）	Screw pitch length S（mm）	Inclination angle θ
102	43	1050	80	0
Soil				
Average particle size of the medium particle d_p（mm）		Medium particle porosity n		
0.001		0.38		

$$Q=\frac{-b+\sqrt{b^2-4ac}}{2a}=\sqrt{360000\cdot\frac{\pi^2 d^4 v_f^2(1-n)^2}{d_p^2}-112\frac{d_p g n^3\pi^2 d^4}{(\frac{L_2}{S})\left[(\pi D)^2+S^2\right]^{0.5}(1-n)}\cdot(L_2\sin\theta+H_o+\frac{D}{2}\cos\theta-H_j)}-\frac{75(1-n)v_f\pi d^2}{7d_p} \quad (8)$$

2.3 Establishment of theoretical seepage model in the shield pressure chamber-screw conveyor

By using the boundary conditions at the interface between the pressure chamber and screw conveyor, the actual flow discharge can be obtained. At the interface of the pressure chamber and screw conveyor, the water head and flow discharge are the same. Based on the numerical solution of pressure chamber seepage and the analytical solution of screw conveyor seepage, the actual flow is determined. As shown in Fig. 8, the intersection of the two curves (H_i, Q_i) is the water head and flow rate of the screw conveyor in the actual seepage process.

By conducting 1:10 physical model test, Merrit and Mair (e.g., Zhu *et al*. 2004, Merritt and Mair 2006, Merritt and Mair 2008) explored the relationship between the water head at the screw conveyor and length of screw conveyor. The screw conveyor is filled with London clay, and a constant pressure of 200 kPa is applied at the earth pressure chamber, corresponding to water head of 20 m. Table 2 summarizes the model geometry parameter and soil permeability coefficient. The measured results reported by Merrit and Mair are used to verify the proposed solution. It is shown that the total pressure and water head in the screw conveyor decreases approximately linearly with the length of the screw conveyor. Based on the model test, the water head at the inlet of the screw conveyor is about 17 m. By substituting this water head into the analytical solution, comparisons between the measured and computed results are shown in Fig. 9. It is shown that the calculated results from the analytical solution have a good agreement with the computed ones. It is indicated that the proposed theoretical seepage model for pressure chamber-screw conveyor is reasonable. The water head along the length of screw conveyor is also compared in this figure. The length of screw conveyor is L_2, and the expanded length (L_z) of screw conveyor is calculated as $L_2/\sin\alpha$. It is found that the reduction rate of water head from the Merrit is higher than that obtained from the analytical solution. But the discrepancies between the measured and calculated results are acceptable. This is because the actual geometry of spiral blade causing a reduction in the water head loss in local areas.

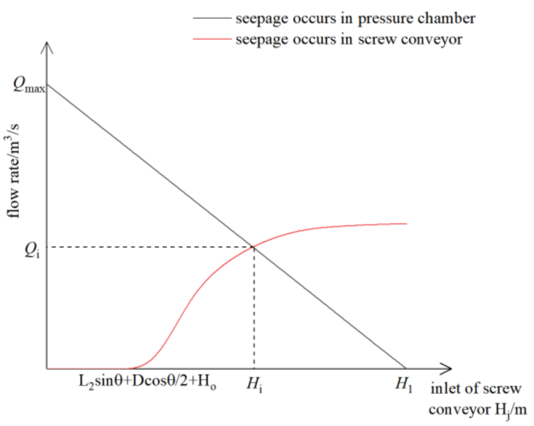


Fig. 8 Theoretical solution diagram of pressure chamber-screw conveyor

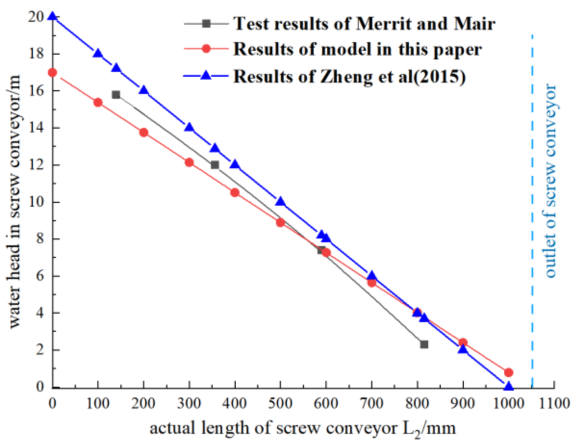


Fig. 9 Comparison between theoretical model and Meerit laboratory test

Table 3 Statistical table of permeability of various soil and mechanical parameters of shield machine

Soil permeability				Mechanical parameters of shield machine	
The soil category	Average particle size（mm）	Particle porosity	Permeability coefficient（m/s）	Length of pressure chamber（m）	2.6
Gravel	5	0.3	1×10^{-2}	Diameter of pressure chamber（m）	6.2
Coarse sand	1	0.35	1×10^{-3}	Length of screw conveyor（m）	10.7
Medium sand	0.3	0.39	1×10^{-4}	Diameter of screw conveyor（m）	0.7
Fine sand	0.09	0.41	1×10^{-5}	Screw pitch of screw conveyor（m）	0.6~1.0
Silty snad	0.01	0.42	1×10^{-6}	Diameter of shaft rod（m）	0.3

3. Analysis of influencing parameters on seepage of screw conveyor

According to Eqs. (7) and (8), flow in the screw conveyor is greatly affected by water head at the tunnel face, permeability coefficient of soil, size of pressure chamber and geometry of screw conveyor. Based on previous study (e.g., Zhu *et al.* 2004, Merritt and Mair 2006, Merritt and Mair 2008), the outlet flow of the screw conveyor is almost regardless of the size of pressure chamber. In practice, the size of pipe inside screw conveyor cannot be adjusted since there are strict requirement of soil discharge efficiency of the screw conveyor. Thus, the influence of the size of pressure chamber and pipe inside screw conveyor is not considered in this study.

To effectively evaluate the spewing, soil permeability and clear distance between screws are two key parameters affecting flow in the screw conveyor. Table 3 summarize the parameters considered in the parametric study. Effects of water head at tunnel face, soil permeability and length of screw conveyor on spewing are considered. A typical soil stratum consisted of silty clay, silty sand, fine sand, medium sand, coarse sand and gravel is considered in this study. The permeability coefficients of these soils are listed in Table 3.

The water head applied at the tunnel face is 10 m, 15 m, 20 m, 25 m, 30 m, 40 m and 50 m (The water heads are all the head at the top of the shield tunnel, and the boundary settings of the excavation surface head are consistent with Section 2.1), respectively. Five clear distances between screw pitch (0.6 m, 0.7 m, 0.8 m, 0.9 m, and 1.0 m) are considered.

3.1 Effect of permeability coefficient of soil on seepage in shield pressure chamber-screw conveyor

Fig. 10 shows variations of flow rate with soil permeability and water head. For this scenario, the clear distance between the screw pitch is 0.8 m. It can be seen that the flow rate increases as an increase in the permeability coefficient. When the permeability coefficient is 1×10^{-3}m/s, the Reynolds number under the water head of 50 m is 8.512. By increasing the permeability coefficient to 1×10^{-2} m/s, the Reynolds number under the head of 10 m is 45.75. Based on the permeability coefficient, the water flow can be classified three types. When the permeability coefficient is less than 1×10^{-3} m/s, the seepage state is laminar flow. By increasing the permeability coefficient to 1×10^{-2} m/s, the seepage state is turbulent flow. When the permeability coefficient is in a range of 1×10^{-3} ~ 1×10^{-2} m/s, the seepage state is a transition state from laminar flow to turbulent flow.

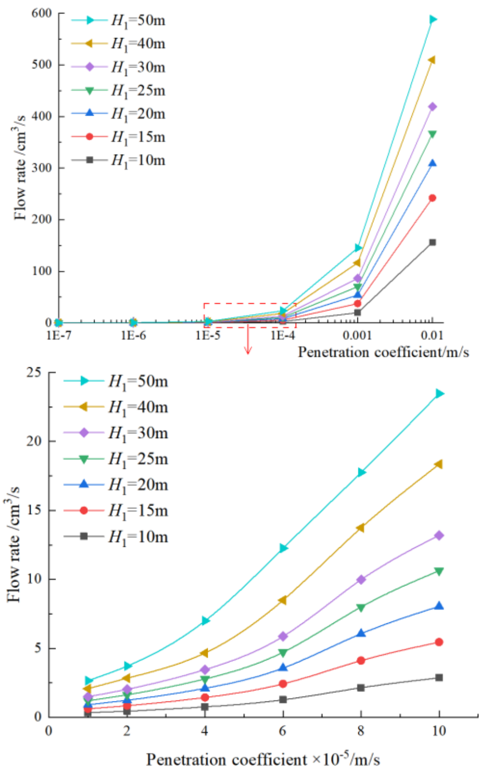


Fig. 10 Relationship between seepage flow and permeability coefficient

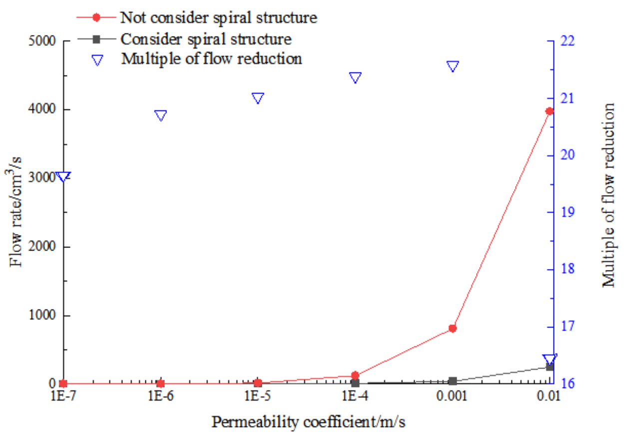


Fig. 11 Comparison diagram of considering spiral structure and not considering spiral structure

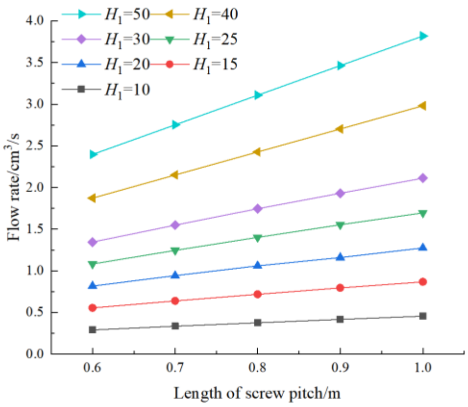


Fig. 12 Relationship between seepage flow and pitch length of screw conveyor

When the ground water head is 20 m, the water discharges of soil with permeability coefficient is 1×10^{-4} m/s and 1×10^{-3} m/s are 53.5 cm^3/s and 73.2 cm^3/s, respectively. As the permeability coefficients of soil are reduced by one order of magnitude, the corresponding water discharge become 1.05 cm^3/s and 9.45 cm^3/s. When the permeability coefficient is small, the flow gradient is larger. As an increase in the average particle size of soil increases, the permeability coefficient of soil increases as well. The fluid subjected to inertial force is expected to larger than the viscous force.

3.2 Effect of structural characteristics of screw conveyor on seepage

Fig. 11 shows the effects of spiral structure on seepage.

In this scenario, the water head applied at the tunnel face is 15 m. Without consideration of spiral structure, the calculated discharge is substantially larger than that considering spiral structure. The calculated discharge in former case is about 21 times of the latter case. This is because consideration of spiral structure increases the flow path of soil and then reduce the overflow section area. When the permeability coefficient is 0.01 m/s, calculated discharge without consideration of spiral structure is only 15 times of that considering spiral structure. The Reynolds

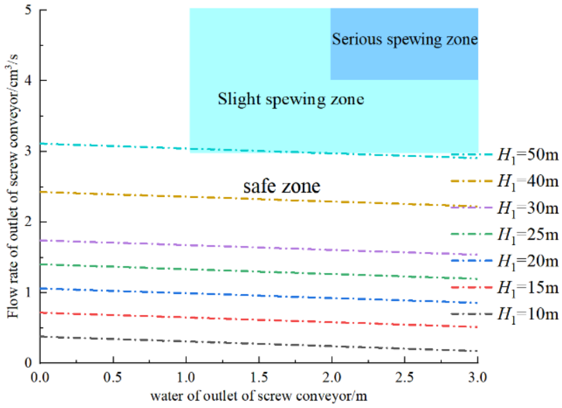


Fig. 13 Spewing occurrence condition diagram

number calculated under this condition is 183, indicating that the seepage state inside the screw conveyor has entered turbulence. In this condition, the inertial force is much large than viscous force. From the previous analysis, the discharge has a linear relationship with permeability coefficient K^a (a less than 1) is linear, the differences between the two calculation results are thus greatly reduced compared with the difference of laminar flow state.

It is found that the spiral structure has great impacts on the seepage in the screw conveyor. Moreover, the spiral structure is controlled by the clear distance between screw pitch. Thus, this study explores the effects of the clear distance between screw pitch on water flow. In this scenario, the permeability coefficient of soil is 1×10^{-5} m/s, other parameters are the same as shown in Table 3. Under a given permeability coefficient, the discharge at the outlet of screw conveyor is proportional to the clear distance between screw pitch, as shown in Fig. 12. Since the total length of the screw conveyor is the same, a large clear distance between screw pitch means that the number of screws is small. Thus, the total length of screw conveyor after expansion is reduced. In order to prevent spewing, the clear distance between screws could be appropriately reduced. Considering that the strength of screw conveyor is limited, it means that there is a certain lower limit for the screw pitch reduction.

4. Discussion on criterion use to evaluate spewing at the outlet of screw conveyor

Based on the research findings in literature (e.g., Merritt and Mair 2006, Merritt and Mair 2008, Talebi *et al.* 2014, Zheng *et al.* 2015, Zhao *et al.* 2015, Peila *et al.* 2007), the spewing at the outlet of screw conveyor is controlled by outlet flow discharge and water pressure head. Because of compression effects of the screw conveyor and discharge gate, Zhu *et al.* (2004) found the screw conveyor can sustain pressure head of 1 m and flow velocity of 3 cm^3/s. If water pressure head or flow velocity is less than the proposed value, there is no any spewing. If water pressure head and flow velocity are higher than 2 m and 4 cm^3/s, serious spewing occurs, while the remaining conditions consider as slight spewing.

In practice, spewing is not easy to occur during advancement of earth pressure shield tunneling. In general, spewing is commonly occurred during suspension of tunnel construction. This is because spewing is the dynamic process of ground water flow to tunnel shield. During tunnel excavation, ground water cannot easily concentrate around the shield tunnel. However, suspension of tunnel construction cause water concentrated around the tunnel shield, spewing of the screw conveyor is commonly observed as a result of restarting tunnel excavation. Fig. 13 shows the criterion used to evaluate spewing for soil permeability coefficient of 1×10^{-5} m/s and screw pitch of 0.8 m. When the water head at the outlet of screw conveyor is 0, the flow reaches the maximum value. As an increase in the water head at the outlet of screw conveyor, the flow discharge gradually decreases. It is indicated that spewing can be avoided in the majority conditions when the permeability coefficient of treated soil is less than 1×10^{-5}m/s.

Because of complex construction condition and soil stratum, it is difficult to obtain the instantaneous flow at the outlet of the screw conveyor. Instead, the average flow at the outlet of the screw conveyor is used. Thus, it is difficult to use results shown in Fig. 13 to directly evaluate the spewing. In practice, the permeability coefficient of muck can be easily determined. The spewing is commonly prevented by decreasing permeability coefficient to a low value. Thus, the criterion used to evaluate spewing based on permeability coefficient of soil is established, as shown in Fig. 14.

It is found that the critical permeability coefficient used to suppress spewing is reduced as an increase in the water head at the tunnel face. In other words, the higher the water head, the smaller the permeability coefficient. As an increase in the screw pitch, the critical permeability coefficient corresponding the occurrence of spewing is reduced. A large screw pith results in a reduction in the length of the expanded screw, causing a shorter seepage path. Under the same water head difference between the tunnel face and the outlet of the screw conveyor, small seepage path gives large hydraulic gradient. Based on the Ergun equation, a high hydraulic gradient gives high flow velocity. Thus, the critical permeability coefficient needs to reduce to an even small value to prevent spewing when the flow velocity is high. Three zones, namely safe zone, slight spewing zone and serious spewing zone are identified in Fig. 14. If soil permeability coefficient falls in the serious spewing zone, the muck soil needs to treat greatly to reduce soil permeability. In contrast, a slight reduction in the permeability coefficient is required if the soil permeability coefficient falls in slight spewing zone. Of course, treatment is not required if the soil permeability coefficient falls in safe zone.

Under similar mechanical parameters of the shield machine and water head at the tunnel face, the critical permeability coefficient soil obtained in this study is about one order of magnitude different from the published results (e.g., Zhu *et al.* 2004, Merritt and Mair 2006, Merritt and Mair 2008). This is because the above calculated results consider the spiral structure of the screw conveyor. Accordingly, water flow path is reduced, and overflow section area is decreased as well. Consequently, the critical permeability coefficient is decreased.

It should be noted that the calculation method for the expansion of screw conveyors is related to actual construction. When shield machine works in the sand stratum or sand-pebble stratum, separation of soil and water can be easily occurred, which go against the assumptions made in this study. Thus, the proposed method is not applicable for this situation. On the contrary, when shield machine works in soft soil stratum, soil and water moves together. Thus, the seepage path of water is the same as the path of soil discharge followed by the spiral line. For a given permeability coefficient of soil, the water flow rate without consideration of structural characteristics of screw conveyor is greater than that considering structural characteristics. Consequently, spewing is more likely to occur. When soil is under good condition, the occurrence of spewing is greatly overestimated if structural characteristics are not considered. Definitely, the construction cost used to prevent spewing increases substantially. Therefore, it is necessary to consider structural characteristics of screw conveyor in the evaluation of spewing.

5. Conclusions

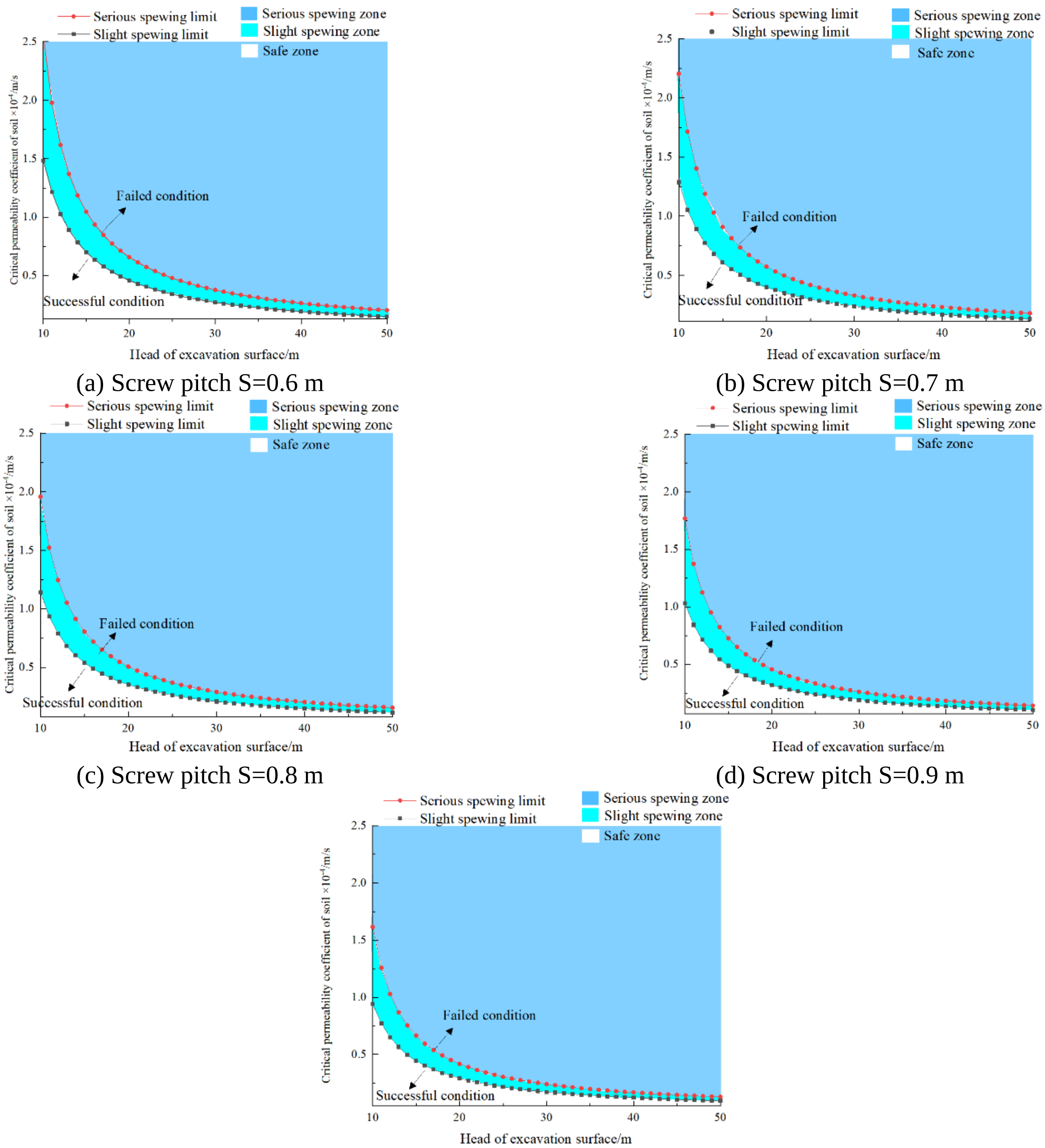
In this study, soil seepage model of pressure chamber-screw conveyor is established to evaluate spewing. Theoretical formula is proposed to calculate flow discharge at the outlet of screw conveyor under various conditions. Based on the computed results, the following conclusions are drawn:

1) By considering structure characteristics of screw conveyor and turbulent flow at the end of screw conveyor, a theoretical seepage model of soil in the screw conveyor is established. Experimental test results are used to verify the rationality of the proposed model.

2) The outlet flow of screw conveyor is greatly affected by screw pitch and permeability coefficient of soil. As the pitch and the permeability coefficient of soil increase, the outlet flow gradually increases and the possibility of spewing increases. Compared with the screw pitch, the outlet flow of screw conveyor is more sensitive to permeability coefficient of soil. When the permeability coefficient of soil is less than 1×10^{-3} m/s or higher than 1×10^{-2} m/s, the groundwater flows are classified as laminar and turbulence flows, respectively. For the remaining permeability coefficients, the groundwater flow transmits from laminar flow to turbulence flow.

3) Based on the established seepage theoretical model, criteria used to evaluate spewing are proposed. The higher the water head at the tunnel face, the smaller the critical permeability coefficient of soil. When the water head applied at tunnel face reaches 40 m and 50 m, the critical permeability coefficients of treated muck should be less than 10^{-5} m/s to avoid spewing. Considering many uncertainties in the construction site, it is suggested that the designed permeability coefficient of the treated muck should be one order of magnitude smaller than the critical permeability coefficient.

4) The spiral structure of the screw conveyor increases the seepage of groundwater in the soil, so it greatly reducing the possibility of spewing. For a given



(e) Screw pitch S=1.0 m

Fig. 14 Critical spewing occurrence condition diagram(Water head in outlet is 0)

permeability coefficient of soil, the water flow rate is overestimated if structural characteristics of screw conveyor is not considered. Consequently, the occurrence of spewing is greatly overestimated, which increases construction cost substantially.

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