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Study on the earth pressure distribution of excavation chamber in EPB tunneling

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ABSTRACT: In shield tunneling, the excavation stability is very important. The balance pressure which supports the work face is offered by the the mucks in the earth chamber. The ideal supporting pressure on the excavation face is trapezoidal. In fact, the pressure is irregular. So, the conceptions of earth pressure supporting ratio (*EPSR*), regular modulus of earth pressure and buffer ability of chamber are put forward. Earth pressures in two different situations of shield tunneling in clay ground and cobble sand ground are studied. The studies show that EPSR and regular modulus of earth pressure in soft ground are both better than those in cobble ground. EPSR and regular modulus of earth pressure are two appropriate assessing indexes for EPB tunneling.

1 INTRODUCTION

With the advantages of surrounding influence, excavation speed, structure quality, working environment etc., the shield tunneling method is popularly applied in the tunnels of metro, railway, road, municipal engineering and so on.

Earth pressure balance machine (EPB) and slurry shield tunneling are the two mostly common method in metro tunnels. Comparing with slurry shield method, the EPB has the merits of small construction yard, less cost, simple technology. So the EPB is more popular in metro tunnels.

EPB machine applies pressure to working face by the mucks which are cut from the face sometimes with injection of soil conditioning additives. With the pressure the working face can maintain stable. The stability of working face is a key factor in the EPB tunneling. The accidents brought by destabilization of working face are the main accidents according to statistics (Qin Jianshe, 2005).

Present researches about the shield tunneling pressure mainly focus on the theoretical pressure needed for the working face (Anagnostou G, Kov'ari K., 1996; Abdul-Hamid Soubral, 2000 & Qin Jianshe, 2005). As for how to apply the pressure and the pressure properties are seldom mentioned and researched. In this research, features of working face pressure, distribution of pressure in the excavation chamber and the pressure in the clay and cobble sand strata are researched. Some conceptions are put forward, and principles are summarized.

2 CLASSICAL EPB THEORY

The excavating system of EPB machine is composed by shield, cutter head embedded with cutters, working chamber, pressure wall, screw conveyor, and thrust cylinders (see Fig 1). When excavation, thrust cylinders apply force to pressure wall, and the pressure wall applies the pressure to the working face by the mucks in the earth chamber. The pressure is used to balance the water and soil pressure in ground.

EPB machine adjusts pressure to balance water and soil pressure in working face by the manners of changing the pressure of thrust cylinders and the rotation speed of screw conveyor (see Figure 1). When it is necessary to increase the pressure in earth chamber, the rotation speed should be decreased and the thrust force should be increase vice versa.

Classical earth pressure assumes these:

1. The pressure applied by shield machine to the working face is trapezoidal. And the trapezoidal pressure balances with the water and soil pressure in working face in order to maintain facing balance.
2. The pressure applied to the ground is equal to the pressure in the pressure wall (M. Herrenknecht & U. Rehm, Aug, 2003). So, the working face pressure is acquired through the pressure values shown in the operating panel.

Obviously, the conditions for classical earth pressure are satisfied with the followings:

1. The mucks in earth chamber should have the properties of ideal plastic fluidity.

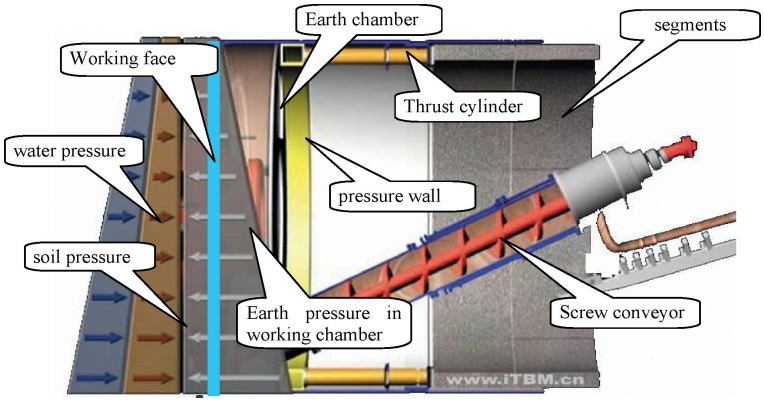

Figure 1. Soil pressure + water pressure = earth pressure in working chamber (Wassmer, Treceno & ANdreossi, 2001).

2. The opening rate of cutter head is enough.
3. There is no pressure loss in the screw conveyor.

In fact, EPB can't reach this ideal state in the practice of excavation.

3 DEFINITIONS RELATED EARTH PRESSURE

The pressure applied by shield machine is related to the stability of working face directly. In practice, it's hard to observe and gauge the pressure of the working face. So, some indirect ways to estimate the pressure of working face, as below:

1 The pressure sensor in the pressure wall. This way is thought as the most efficient way. But it has difference between the two pressures.
2 The force of thrust cylinders and the torque of cutter head. They increases with the earth pressure increase;
3 The volume of mucks discharge. More discharge, less earth pressure.

For further research, the following definitions are given:

3.1 *Earth pressure supporting ratio (EPSR)*

The classical earth pressure theory assumes that the supporting pressure on the working face is supplied by earth in the earth chamber (see Fig 1). In fact, the supporting pressure is composed by two parts: earth in working chamber and the plane of cutter head. As to the Figure 2, the earth pressure is mainly transferred though the open of cutter head. But the plane also contributes supporting pressure. So the earth pressure supporting ratio (*EPSR*) is defined as the ratio of earth pressure in the total supporting pressure.

$$EPSR = \frac{\text{earth supporting pressure}}{\text{total supporting pressure}} \quad (1)$$

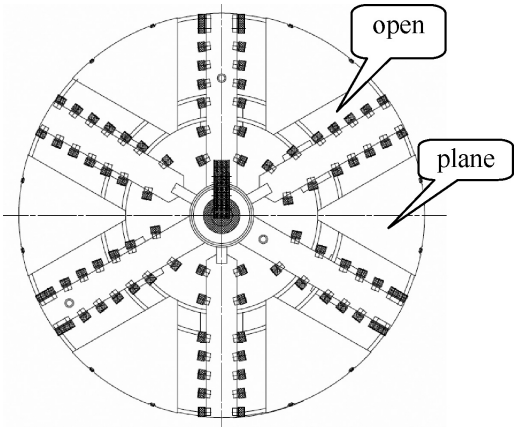

Figure 2. Schematic plan of open and plane.

where *EPSR* = Earth Pressure Supporting Ratio;
earth supporting pressure: the total pressure of earth pressure on the working face;
total supporting pressure: the total supporting pressure on working face including earth pressure and cutterhead plane supporting pressure;

The total supporting pressure is assumed the balance pressure on the working face.

The ratio is related to the shape of cutter head, opening rate and the control of earth pressure. The value of the ratio is between 0 and 1 which indicates the state of earth control when excavating. For example, the ratio of cutter head of spoke shape is bigger than that of plane shape.

3.2 *Regular modulus of earth pressure (RMEP)*

Five pressure sensors are located on the pressure wall (see Fig 1). The position of the sensors are shown in Figure 3, and the height is shown in Table 1.

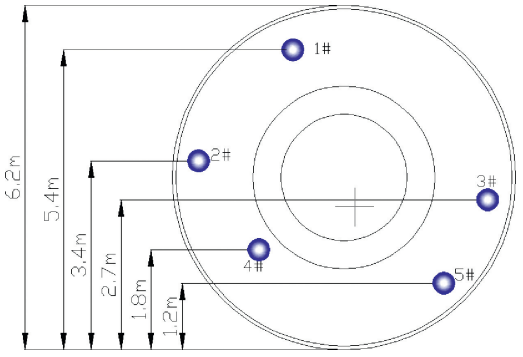

Figure 3. The Distribution of earth pressure sensors.

Table 1. Position of the sensors.

Sensor No.	1	2	3	4	5
Position(m)	1.2	1.8	2.7	3.4	5.4

The regular modulus of earth pressure *RMEP* is used for indicating the regularity of the earth pressure in working chamber. The value of *RMEP* is defined as related coefficients: R^2 between values of earth pressure and the corresponding vertical position. The value of the modulus is between 0 and 1 which indicates the fitting extent of the fitted regression line. The ideal value is 1. The value is closer to 1, better regular of the earth pressure is.

$$R^2 = 1 - \frac{SSE}{SST} \tag{2}$$

where

$$SSE = \sum (Y_i - \hat{Y}_i)^2 \tag{3}$$

$$SST = (\sum Y_i^2) - \frac{(\sum Y_i)^2}{n} \tag{4}$$

Y_i: actual data points of earth pressure

$\hat{Y}_i$: predicted value of the regression model

The detail definition of R^2 can referred Richard A. Johnson (1992).

3.3 *Buffer ability of working chamber*

It can't keep the balance pressure when the mucks in the working chamber are over discharged due to improper operation. The volume of the working chamber should have the ability of maintaining the pressure due to improper discharging operation. So the chamber should buffer the earth pressure when the mucks are sudden loss.

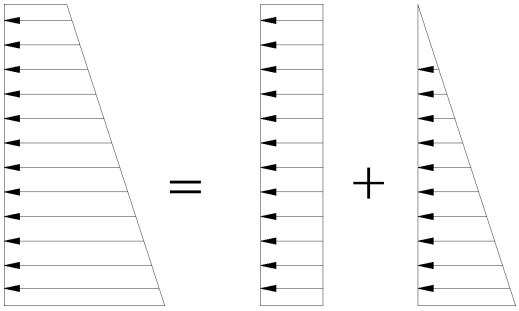

Figure 4. Total pressure makeup: additive pressure of facing + lateral pressure of mucks.

Here, the buffer ability of chamber is defined as the proportion of discharged mucks in the whole chamber at the condition of screw conveyor working for 5 minutes with maximum rotation speed.

$$\text{buffer ability} = \frac{\text{discharge vol. in 5 min.}}{\text{vol. of working chamber}} \tag{5}$$

It is deemed that the buffer ability is good if the proportion of discharge mucks is less than 30%.

4 PROPERTIES OF EARTH PRESSURE OF EPB EXCAVATION

4.1 *Analysis of pressure makeup*

The pressure wall is in the behind of working chamber. The wall undertakes the main face pressure. Here the series S type EPB shield machine of Herrenknecht are take an example to research the wall pressure. The earth pressure sensors in the wall are distributed as the Figure 3. There are five sensors in the wall. The serial number and the position are shown in Figure 3.

The measured pressure shape is trapezoidal in most common situation (see Fig 1 & Fig 4). The trapezoidal pressure is composed of two parts: one is rectangular and another is triangular. The triangular can be deemed as the lateral pressure of the mucks, and the rectangular can be deemed as the additive pressure applied by the water and soil pressure of the working face.

Analysis hereinbefore, there won't be additive pressure if the pressure shape is triangular. At this situation, if the thrust force is big and the face is stable, the cutter head will undertake large portion of face pressure. So, the earth pressure support ratio *EPSR* is low which lead to the large contact stress between cutter head and face and large torque of cutter wheel. Usually, in this situation, the wear of cutters and cutter head are serious.

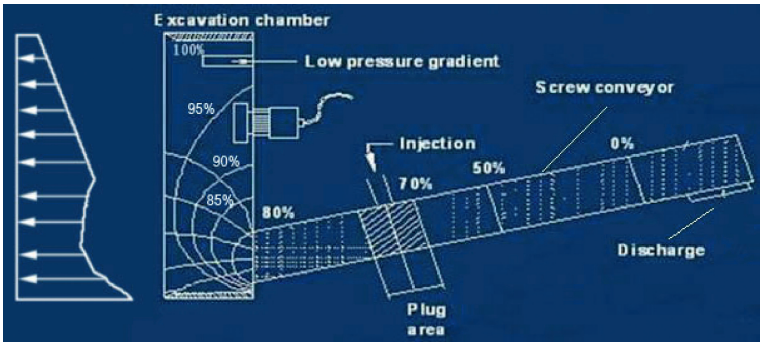

Figure 5. Earth pressure distribution diagram (Herrenknecht & Rehm, 2003).

Table 2. The ground parameters of Guangzhou.

ρ (g/cm^3)	w(%)	e	c(kPa)	Φ(°)	Es1-2(MPa)
1.95	31	0.8	22.8	18.1	4.7

4.2 *Pressure properties in clay*

Usually, the mucks of clay strata have a good plastic fluidity which can apply a regular pressure to the excavation face. So, the earth pressure supporting ratio is high; and the modulus of the earth pressure is high too. The stability of working face can be well controlled if the working chamber satisfies the mucks buffer.

Nevertheless, there is pressure loss in the screw conveyor in this kind of strata. The pressure gradient curve is shown in Fig 4. It is inevitable that pressure falls in the screw conveyor because the pressure is 0 in the discharging outlet. The pressure gradient depends on the fluidity and impermeability of the mucks. The pressure in the inlet of screw conveyor has fallen to 80% (see Fig 5). It indicates that the pressure isn't regular due the existence of screw conveyor though the mucks is of plastic fluidity. (see left in Fig 5)

The excavation data of ring No. 219 in one section of line 5 of Guangzhou metro are taken for an example. The cutter head of the EPB machine is plane type, and opening rate is about 28%. There are two types of cutters: disc cutter and scrape cutter. The length of working chamber is 1 m. The position of earth pressure sensors are shown in Figure 3. The tunnel is in the stratum of <4 – 2> whose main parameters are shown in Table 2.

The Figure 6 is the figure of earth pressure data which are acquired from the earth pressure sensors in pressure wall. The number order of the pressure sensors is from the top down. They are 1#, 2#, 3#, 4# and 5#. From the data it can obtain that the regular modulus of earth pressure *RMEP* is about 0.98. This value shows the earth pressure of pressure wall is more regular.

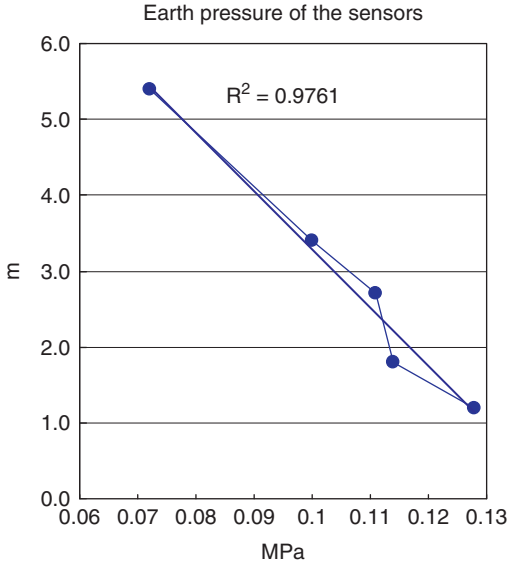

Figure 6. Mean earth pressure in the pressure wall.

Table 3. Assessment of earth pressure supporting ratio.

Actual torque/ Max. torque	Additive stress/ Max. stress		
	0 ~ 30%	30 ~ 50%	>50%
<0.8	<0.5	0.5 ~ 0.8	>0.8
>0.8 <1.1	<0.3	0.3 ~ 0.5	>0.5
>1.1	<0.1	0.1 ~ 0.3	0.3 ~ 05

The proportion of earth pressure and cutter head is hard to be divided. The earth pressure supporting ratio can't be calculated precisely. So, it can be judged by the earth pressure in the pressure wall and the torque of cutter head by the following way. The additive

Table 4. Main index of the EPB (S365).

Machiner type	Excavation diameter(m)	Rating torque(KN·m)	Max. thrust(kN)	Max. speed(mm/min)	Opening ratio	Cutter head
EPB TBM	6.28	5980	34210	80	28%	disk and scrape

Table 5. The indexes of the stratum.

ρ(g/cm^3)	w(%)	c(kPa)	Φ(°)	E_0(MPa)	K(m/d)
2.2	31%	0∼1	38	45	27

pressure can be known from the pressure wall. Because the additive pressure is applied by face, higher additive pressure, higher earth pressure supporting ratio. If the cutter head plate undertakes more facing pressure the torque of the cutter head will become bigger. According to empirical summary and modification, the method using additive pressure and torque to estimate earth pressure supporting ratio is put forward. (shown in Table 3)

The actual torque of this ring is 3650 kNm while the rating torque is 4500 kNm. The value of actual torque/rating torque is 0.81; and the value of additive stress/max. stress is 0.32. So according to the earth pressure and the torque and assessing by the Table 3, the *EPSR* is about 0.65.

4.3 *Pressure properties in cobble sand strata*

The line 1 of Chengdu metro is in strata of cobble and sand. The EPB machine is Φ6.28 m of Herrenknt. The main parameters of the machine are shown in Table 4.

From the analysis hereinbefore, the *EPSR* is about 0.6 ∼ 0.7 in the soft clay strata. And in most of the situations the EPB tunneling can't reach total earth balance in working face. The values of *EPSR*s are usually controlled bigger than 0.5. The main balance pressure is earth in this stratum. The regularity of the earth pressure is good. The regular modulus of earth pressure reaches 0.98.

The tunnel line is in the strata of cobble and sand. The cobble content is high and the permeability coefficient is high. The main indexes of strata <3 – 7> are listed in Table 5.

The pressure data in the Figure 7 are collected in the ring of 112 which is the mean value in the ring. And the torque of cutter head is 3020 kNm in this ring. The *EPSR* is about 0.4 from the Table 3 and Figure 7.

The regular modulus of earth pressure *RMEP* in the chamber is 0.93 which is less than the value in clay. The pressure gradient can reflect the muck unit weight. The gradient value is the product of unit weight and lateral

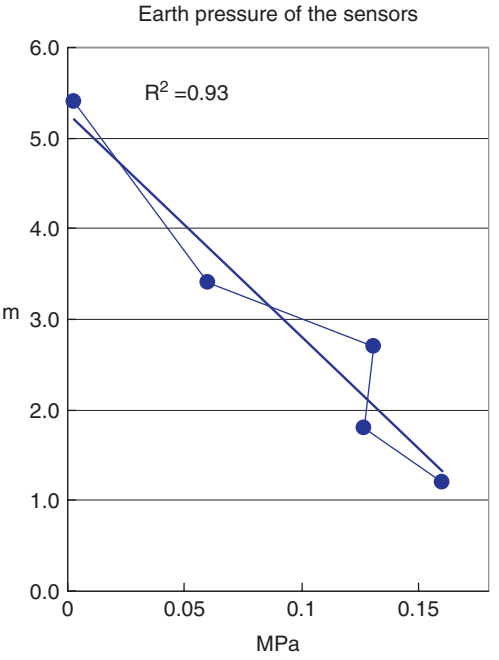

Figure 7. Mean earth pressure in the pressure wall.

pressure coefficient. Due to the irregularity of earth press in cobble and sand strata, it's hard to calculate the unit weight. However, it shows the unit weight is bigger according to Figure 6 and Figure 7.

The data show that the *EPSR* is low. So the cutter head plate will undertake bigger pressure. Low *EPSR* is unfavorable for wear of cutters and cutter head. So the *EPSR* should be increased by taking some measures. Such as soil conditioning should be taken to increase the mucks' plastic fluidity. Simultaneously, the regular modulus of earth pressure can be increased.

4.4 *Buffer ability of working chamber*

The discharging ability of the screw conveyor is as below:

$$Q = \eta \frac{\pi}{4}(D_1^2 - D_2^2)Pn \tag{6}$$

where:η- discharging efficiency, if there is no loss, $\eta = 1$. In common η is about 0.9; D_1- inner diameter of screw conveyor; D_2- outer diameter of center shaft; P- Distance of paddle; n- Rotation speed.

According to formula (6) the maximal discharging ability of screw conveyor is 1.2 m^3/min. The volume of discharging is 6 m^3 in 5 min. The cubage of the chamber is about 30 m^3. According to formula (5), the buffer ability is 20% (6/30 = 20%) of the cubage of chamber (shown in formula 7).

$$buffer\ ability = \frac{1.2 * 5}{30} * 100\% = 20\% \quad (7)$$

According to calculation, 30% loss of working chamber volume can cause big ground settlement. The bigger buffer proportion can cause more ground loss and instability of working face. If the proportion is over 30%, it can be deemed that the buffer ability of the chamber is not enough. If it is below 30% it can be deemed that the chamber has the ability of earth pressure buffer for improper operation.

5 CONCLUSIONS

From the analysis and study of the theory and measured data, the main conclusions are as below:

1 The classical earth pressure theory has limited and premises.
2 The pressure in the pressure wall is divided into two parts: additive pressure of working face and lateral pressure of mucks.
3 The conceptions of earth pressure supporting ratio, regular modulus of working chamber and buffer ability of chamber are put forward to research the pressure properties.
4 Clay stratum and cobble sand stratum are taken for examples to study.
5 The research shows that the actual pressure can't reach the situation of classical pressure.
6 *EPSR* and regular modulus in clay are both higher than in cobble and sand. So the invalid wear is higher in cobble and sand strata.

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