Effect of shield tail void closure on lining earth pressure

Influence de vide fermé de queue de bouclié sur la pression du sol exerçant sur la paroi interne

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ABSTRACT: Shield tunneling method is often used to built a tunnel in soft soil ground. The earth pressure acting on the lining structure may be affected by various conditions, such as the soil properties, overburden thickness, construction technology, etc. This paper introduces a centrifugal test study of the effect of tail void closure on earth pressure to which lining structure is subjected. Test result shows strong arching action of sandy soil and very small earth pressures acting on the tunnel lining due to the tail void closure.

RESUME: La méthode de la construction des tunnels est souvent utilisée pour construire un tunnel dans le sol mou. La pression du sol exerçant sur la structure de paroi peut être influencée par des conditions variées, telle que les propriétés du sol, l' épaisseur des couches sus-jacentes et la technologie de construction, etc. Cet article introduit une étude d'essai centrifuge de l'influence de vide fermé de queue sur la pression du sol que la structure de paroi subit. Le résultat de l'essai montre que plus grande l'action d'arc du sol sableux et plus petite la pression du sol exerçant sur la paroi de tunnel causée par le vide fermé de queue.

1 INTRODICTION

During the shield tunneling, the built-up lining rings are pushed out from the shield tail as its going forward, with the clearance occurring between the ring and cylindrical excavation face, known as shield tail void. Such clearance will close, because of convergence of surrounding soil mass. Actual observations have shown that the shield tail void is one of main factors for shield method to disturb the surrounding soil mass, consequently, causing settlement of ground surface. Because of that the shield tunnel is often built in soft stratum in a city, thus, particular attention is paid to tail void, and pressure grout to it is adopted to reduce its unfavorable consequence. Similarly, in the past studies on the mechanical behaviors of shield tunnel, the effect of tail clearance on surrounding strata was emphasized. Authors have studied the soil mass stability problem caused by shield tail clearance(Atikison J H & Potts D M. 1977. Chambon, P. et al. 1991). However, the effect of shield tail clearance on the lining structure has not been studied sufficiently up to date. In fact, the soil mass around the shield tunnel will experience a complicated stress/strain changing process, including the process of interaction between the soil mass and the lining structure, due to appearance and closure of the shield tail clearance. The shield tail clearance, therefore, will cause a serious influence on the earth pressure finally applied to the lining structure. In view of structural safety and development of structural design theory, the effect of shield tail clearance on the lining earth pressure, in spite of increasing or reducing the earth pressure, is worthy to be studied.

Based on above reasons, authors in this paper have studied this effect using the centrifuge model test. Centrifuge test can reproduce in-situ stress/strain fields in a small model, and would be an ideal mean for studying problems such as underground opening.

This study is conducted in combination with the need of the design of a proposed large water transfer tunnel in China. The tunnel is planned to be built across the Yellow River. Shield tunneling method is considered to construct it at a depth of 20~30m in the sandy soil deposit. The earth pressure which the tunnel may be subjected needs to be determined carefully in design by taking account of various affecting factors, such as the overburden thickness, the geology condition, the lining structure style and the tunneling techniques, etc.

Table 1. Centrifuge test conditions.

δ (mm)	Type of soil	H/D	Water content condition
100	Medium sand	2	Dry sand ground
100	Medium sand	2	Saturated sand ground
200	Medium sand	2	Dry sand ground
200	Medium sand	2	Saturated sand ground
200	Medium sand	3	Saturated sand ground

2 DESCRIPTION OF MODEL AND THE CENTRIFUGE TEST PRINCIPLES

2.1 *Test conditions*

The thickness of overburden above the tunnel and the outer diameter of tunnel in prototype are denoted by signs H and D respectively. In shield tunneling, generally, the shield tail clearance has the shape of crescent. In this study, the height of top of crescent is denoted by the sign δ .

The stratum is simulated with a kind of medium sand, which has average particle diameter of 0.25mm and non-uniformity coefficient of 5.14. Five model tests with different conditions as shown in table 1, were performed. Through these tests, the effect of shield tail void closure on lining earth pressure can be evaluated for different conditions.

2.2 *Model preparation*

Model tests, on plane strain problem, were carried out in 50g-t centrifuge in the testing laboratory of Tsinghua University, with the model box of 600mm×520mm×200mm, the model scale of 100, and maximum centrifugal acceleration of 100g.

In prototype, outer diameter of the tunnel lining, D, is 9.6m, with its thickness of 45cm. The elastic modulus of lining concrete is 35GPa. In test model, outer diameter of the lining is 96mm. The lining concrete is simulated with aluminum alloy. The elastic modulus of the aluminum alloy is 70Gpa. According to bend deformation similitude criteria, the thickness of model lining should be 3.2mm.

Under gravitational field condition, the ground model specimen is prepared with dry density of 17.42kN/m^3, correspondingly to a relative density of 0.65. The lining structure was

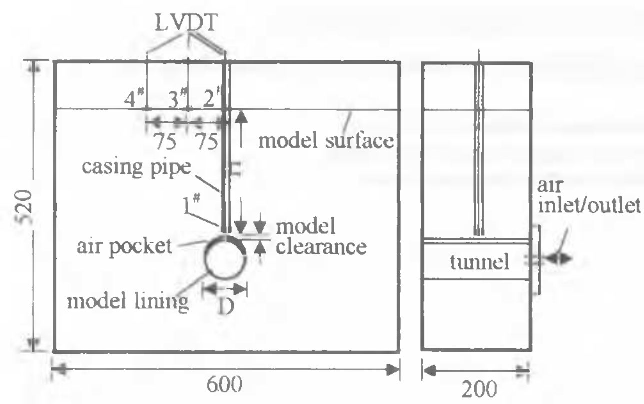


Figure 1. Sketch of 2-D model and its container, in mm

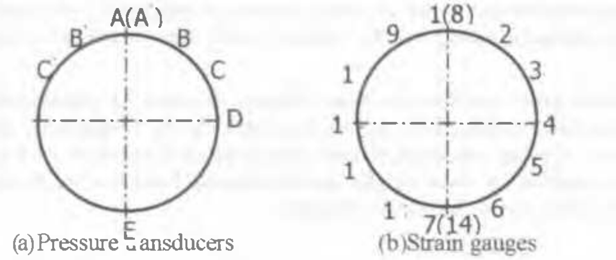


Figure 2. Schematic diagram showing the measured pressure and strain points

placed in its position in the model box, as shown in figure 1.

More specifically, the lining structure model is a cylinder made of aluminum alloy. The aluminum cylinder is coated with an air pocket made of emulsion. The air pocket can be inflated to form a clearance between it and the lining for simulating the shield tail clearance.

On the top of air pocket, point 1# was installed for measuring the vertical displacement at the arch crown of tunnel, and on the model surface, points 2#,3#,4# for measuring the vertical ground surface displacements, see Figure 1.

The vertical line through the center of the round lining structure is taken as reference line. The sign θdenotes a central angle deviating from the reference line. Along the outer surface of the lining structure, at these points where θ=0°, 30°, 60°, 90°and 180°, respectively, miniature pressure transducers are mounted for measuring the earth pressure there, see figure 2(a). Among these transducers, A',B' and C' are parallel measuring points to A,B, and C respectively. At these points where θ=0°, 30°, 60°, 90°, 120°, 150° and 180°, strain gauges are pasted for measuring the lining's strain, see figure 2(b). At points 1~7, strain gauges are pasted both on the inner surface and the outer surface of the lining to measure the bending strain in the circumference section, and at points 8~14, strain gauges are pasted only on the outer surface to measure its outer strain.

After completion of above works, air inflation to the emulsion pocket was made to form crescent-like shield tail clearance, see figure 3. Air pressure for inflation was controlled according to observed value of vertical displacement at the measuring point 1#. When the value equals to the height of the model clearance, inflating work stops immediately. Because of that the model is prepared under 1g gravitational field condition, the required air pressure is very small, slightly more than 10kPa.

2.3 *Test principle*

The centrifuge is operated in three phases. In whole testing process, automatic data acquisition of relevant pressure, strain and displacement was carried out, so as to obtain the values of earth pressure acting on the lining structure and the lining's strain. See

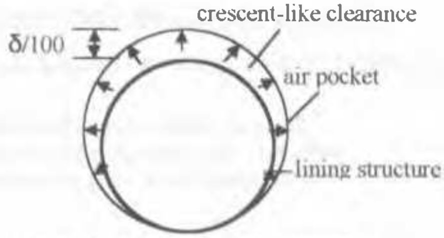


Figure 3. Scheme of model clearance

also figure 4, the characteristics of three phases are as follows:

Phase □—The centrifuge is accelerated gradually until the acceleration of 100g. At the same time, the air pressure in the emulsion pocket is proportionally increased simultaneously to compensate for the increase of overburden pressure to simulate the initial ground stress field. In this phase, the shield tail clearance has the shape of crescent, and no earth pressure is applied on the lining structure.

Phase □—The acceleration keeps constant, equal to 100g, while the air pressure in the emulsion pocket decreases gradually down to zero to simulate the excavation and support pressure reduction process. It can be seen from figure 4 that, while the support pressure drops to a very low value, the measured pressures acting on the miniature pressure transducers suddenly increase and, strains of the lining also increase synchronously. It means that soil mass becomes unstable and converges to the lining, subsequently, the interaction between the soil mass and the lining structure occurs. This low value of support pressure is defined as critical support pressure, P_{cr}, with which the soil mass comes to a critical state. The failure of soil mass results in closure of the shield tail clearance, which further leads to the increase of earth pressure acting on lining and the increase of ground settlement. Finally, the stress/strain states reach stability through soil-lining interaction.

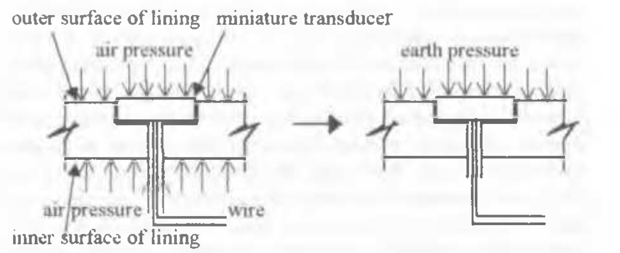
The transformation principle of pressures acting on miniature pressure transducers is shown in figure 5.

Phase □—The centrifuge is decelerated gradually to stop.

3 RESULT ANALYSIS

3.1 *Critical support pressure, P_{cr}*

The values of P_{cr} acquired from tests are listed in Table 2 for



(a) air support pressure acting (b) earth pressure acting without air pressure

Figure 5. Transformation of pressure acting on miniature pressure transducer

each test condition. For dry sand ground, P_{cr} is the measured critical support pressure. For saturated sand ground, P_{cr} is the measured one subtracted by water head above tunnel. It can be seen that the value of P_{cr} is about 1/3~1/5 of the value of overburden weight.

Table 2. Critical support pressure, P_{cr}

δ (mm)	H/D	Water content condition	P_{cr} (kPa)
100	2	Dry sand ground	60
100	2	Saturated sand ground	50
200	2	Dry sand ground	55
200	2	Saturated sand ground	62
200	3	Saturated sand ground	90

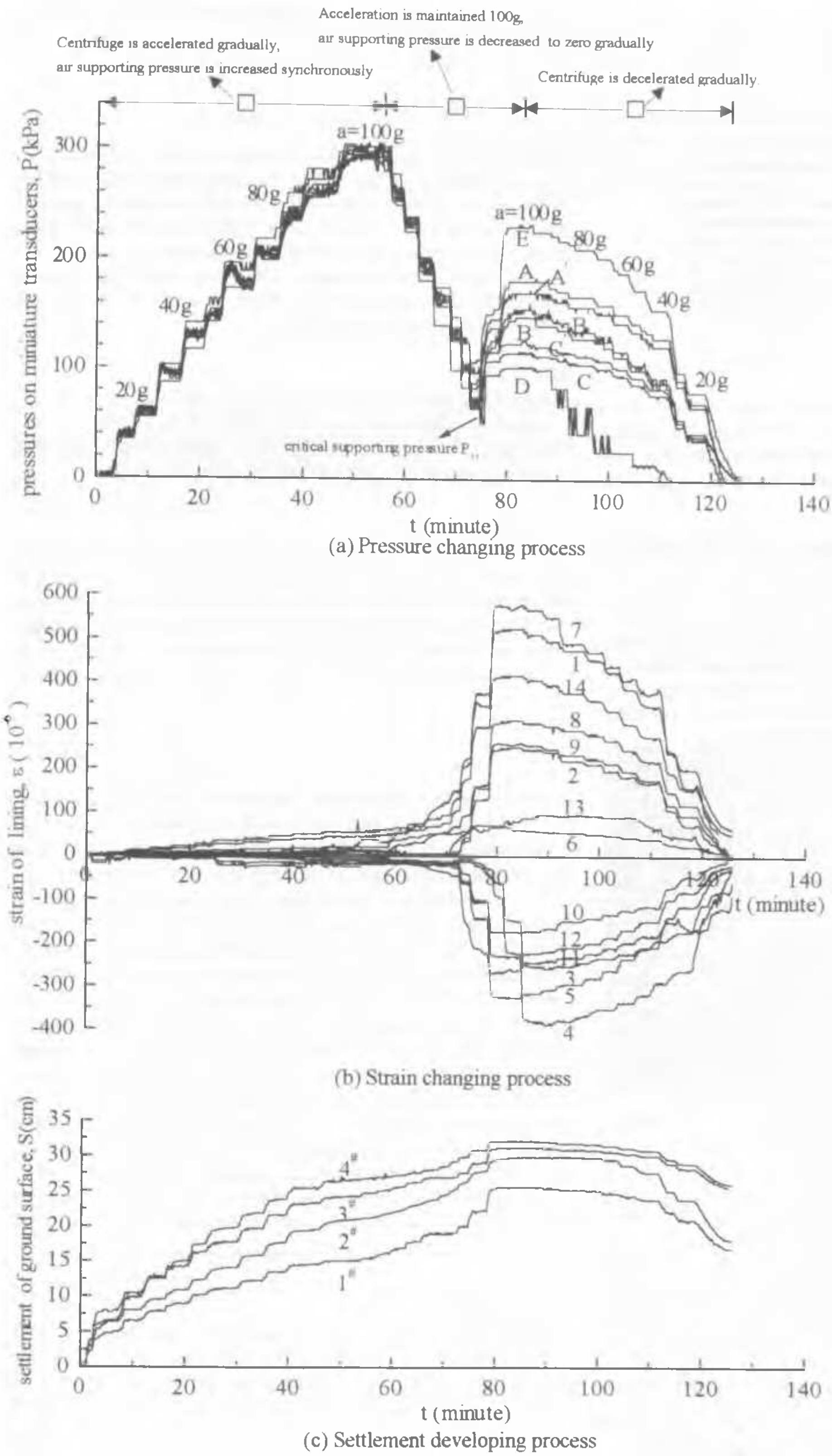


Figure 4. Pressure, strain and settlement measured in centrifuge accelerating and decelerating processes (H/D=2, dry sand ground, δ=100mm)

3.2 *Earth pressure*

The distribution of earth pressure acting on the lining structure after closure of the shield tail clearance and stability of soil-lining interaction is shown in Figure 6. In this figure, P_e is the measured earth pressure, P_{e0} is the calculated earth pressure under the initial K_o state of the intact ground. The effective friction angle φ of the sand is of 36°. The formula for coefficient of earth pressure at rest, is:

$$k_0 = 1 - \sin\varphi \quad (1)$$

The formula for normal earth pressure at any point on the lining structure under the initial K_o state, is:

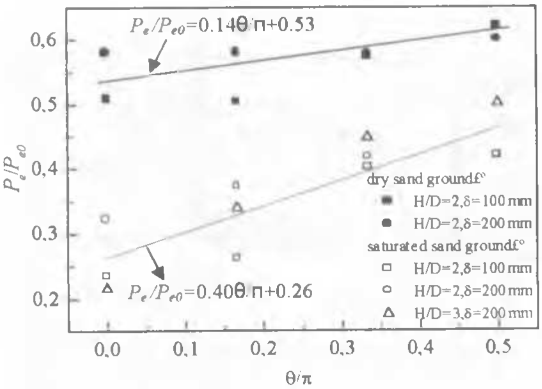


Figure 6. P_e/P_{e0} ~θrelationship

$$P_{e0} = (\frac{1+k_0}{2} - \frac{1-k_0}{2}\cos 2\theta)\gamma' z \qquad (2)$$

Where γ' is the buoyant unit weight of soil, z is the depth of a calculating point.

For dry sand ground and saturated sand ground, the following relationships can be obtained from figure 6:

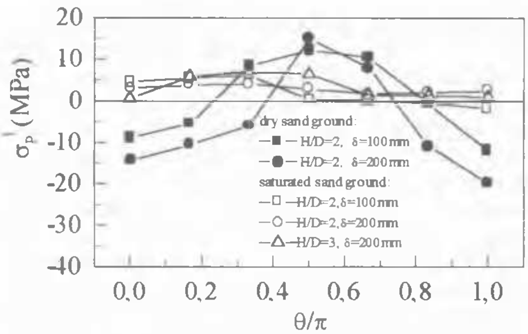
P_e/P_{e0}=0.14θ/π+0.53 (3)

P_e/P_{e0}=0.40θ/π+0.26 (4)

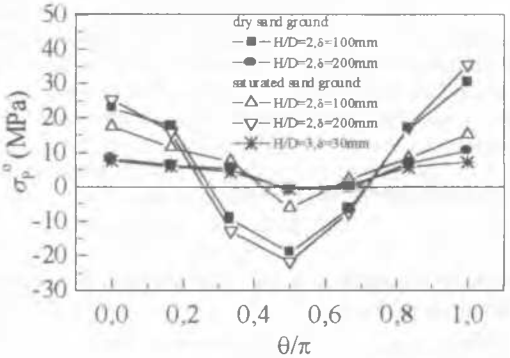
Tested earth pressures are much smaller than the calculated ones of initial K_o state, especially for saturated sand ground. It means that in clearance closing and soil-lining interacting process, the shear strength of soil and the arching effect of soil mass play important roles in reducing the earth pressure.

3.3 *Stress in lining*

Figure 7 shows the distribution of stresses along internal and outer surfaces of the lining structure. Along outer surface, the stresses at top and bottom are compressive, and in the zone near waistline, are tensile. Along inner surface, the distributive zones of tensile and compressive stresses are just opposite from those along the outer surface.



(a) Inner surface



(b) Outer surface

Figure 7. Distribution of stresses in lining structure

4 CONCLUSION

From the test results, the following conclusions are obtained:

(1) The closure of an initial tail void during shield tunneling process activates strong arching effect of sandy soil mass around the tunnel, subsequently leads to very small earth pressures acting on the tunnel, especially for saturated sand ground.

(2) The critical support pressure which is needed to maintain the stability of soil mass around a tunnel, P_{cr}, is very small compared with the overburden weight.

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