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Influence of leakage on tunnel behavior in soft soils

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ABSTRACT: The effect of tunnel leakage on tunnel behavior was studied by small scale model tests in terms of the tunnel settlement as well as lining moment. Both the finite permeable and impermeable water inflow regimes of tunnel lining were considered in the model tests. The influence of tunnel leakage was revealed by the development of tunnel settlement and lining moment with time. The tunnel settlement increases with time when the tunnel is permeable, while the tunnel is lifted when the tunnel is impermeable. The magnitude of tunnel settlement depends on the quantity of tunnel leakage. Longitudinal differential settlements usually arise from tunnel leakage. The lining moments increase with time at tunnel crown and invert when the tunnel is permeable, but the variation of lining moment can be neglected when the tunnel is impermeable.

1 INTRODUCTION

Tunnel leakage has been one of the most problematic technical difficulties widely existing in operating tunnels especially in soft soils as shown in Figure 1. Its unfavorable influence on tunnel structures, waterproofing of joints and normal running of a tunnel has required more attention than ever. The leakage of tunnel usually results in the post-construction settlements of the tunnel (Mair, 2008; Zhang *et al.*, 2005; Shin *et al.*, 2002; O'Reilly *et al.*, 1991). The influence of leakage on the tunnel has been studied mainly using numerical modeling method due to the large timescale of field-based research. This difficulty seriously limits the field monitoring data to be obtained to present the relationship between tunnel permeability and settlements of tunnels and soils. Therefore, the numerical modeling method has been a most powerful way to study the effect of water inflow on the tunnels and soils. O'Reilly *et al.* (1991) firstly introduced the definition of relative permeability of tunnel lining and soils to study the influence of tunnel leakage. The relative permeability was originally presented as the ratio of the lining permeability k_l to the soil permeability k_s. The relative permeability of tunnel lining and soils was extensively employed in numerical modeling to simulate the inflow effect of groundwater on the settlement of tunnel and soils (Zhang *et al.* 2005; Shin *et al.* 2002). Later, Wongsaroj (2005) expressed the relative permeability as a dimensionless number RP defined as $(k_l/k_s)\cdot(C/t_L)$, where C is the clay cover above the tunnel crown, t_L is the thickness of the tunnel lining.

In addition to the numerical modeling method, some analytical solutions are also found in the literature. Carter *et al.* (1982) studied the evolution of stress and settlement of soils around tunnel face with time considering two types of drainage conditions of the tunnel lining, one was fully permeable and the other was impermeable. Later, the time-dependent behavior of soils and the stiffness of lining were taken into account by Carter *et al.* (1983, 1984) to perfect their study described in Carter *et al.* (1982). Based on the studies of Carter *et al.* (1982, 1983, 1984), Li *et al.* (1999) studied the long-term behavior of tunnels considering the finite permeability of tunnel.

All the research found in the technical literature has proved that the relative permeability was the most important factor which controls the behavior of tunnels and surrounding soils when tunnel leakage happened. However, the tunnel lining permeability k_l used in relative permeability was considered to be uniform along the tunnel, which is not always the reality for tunnels with precast segments. Most of the tunnels in soft soils contain the longitudinal and circumferential joints and hand holes. Most of the leakage happened through the joints and hand holes shown in Figure 1 in Shanghai, China. Therefore, the permeability of tunnel lining is not uniform along the tunnel, but it was really difficult to simulate the actual state of tunnel leakage in both numerical modeling and analytical solutions. Considering the limitation of field-based database, the small scale model tests were performed to study the influence of the tunnel leakage on the tunnel and soils.

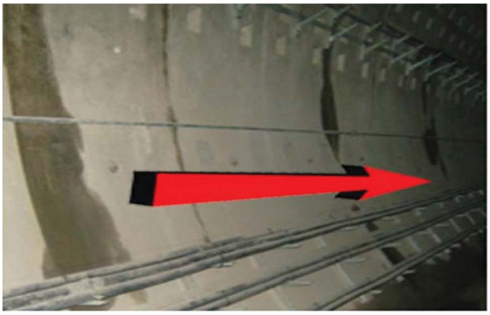

Figure 1. Leakage of shield tunnel in soft soils.

2 TUNNEL MODEL

The tunnel model was designed with the prototype of Shanghai metro tunnel. The prototype tunnel is 6.2 meter and 5.5 meter in external and internal diameter respectively. The thickness of the segment is 0.35 meter. The width of the segment is 1 meter. The tunnel ring was installed by 6 segments namely 1 piece of key segment, 2 pieces of B type segment and 3 pieces of A type segment. The assembly of the tunnel segments was shown in Figure 2. The segments were connected by steel bolts.

The tunnel model was made of high density polyethylene (hdpe) and consists of 6 segments. The segments of tunnel model were cut from the hdpe tube with the division proportion shown in Figure 2. The analogous theory was applied and the similarity scale between practice and model was taken as 38.75 considering the diameter modulus. Both the geometric and stiffness similarity were considered in the tunnel model. The similarity scales were shown in Table 1 and the parameters of model and prototype tunnels were listed in Table 2. The coefficient of stiffness is defined as the ratio between tunnel stiffness with joints and stiffness without joints. The equivalent stiffness of tunnel with joints was applied.

The steel bolts were modeled by screw. The number and size of screw were determined based on the coefficient of stiffness ratio. The segments were staggered installed in the model tunnel. The key segment staggered 22.5° in two rings. Every two rings were a staggered circle. The tunnel model comprised of 50 rings. The tunnel model is shown in Figure 3.

The model test was carried out in a steel container. The steel container is 1.5 meter long, 0.8 meter wide and 0.9 meter high. Six taps were set in two rows at the side of the container. The transparent hose was connected to the taps, so the variation of the water level could be detected from the transparent hose just with rules.

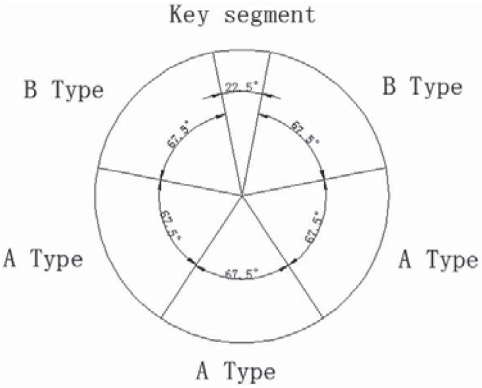

Figure 2. The partitioning of the tunnel segments.

Table 1. The similarity scales between practice and model.

Geometric ratio	Elastic modulus ratio	Coefficient of stiffness ratio	Concentrated load ratio
38.75	29.36	1137.7	44085.88

Table 2. The parameters of model and prototype tunnels.

	External Diameter	Segment thickness	Segment width	Elastic modulus
	m	m	m	MPa
Prototype	6.2	0.35	1	3.45×10^4
Model	0.16	0.0095	0.258	1175

Figure 3. The assembly of the tunnel segments.

3 PROCEDURE OF MODEL TEST

3.1 *Monitoring devices*

The water level, the lining stress as well as the settlements of the tunnel were monitored during the model test. The water level could be detected through the transparent hose with rulers shown in Figure 4. The stress of lining was measured by strain gauges. The strain gauges were set on two rings of No. 26 and No. 37. The tunnel model was numbered from No. 1 to No. 50 from one end to the other. The distribution of strain gauges on each ring is shown in Figure 5.

The neutral axis of the lining during bending was supposed to coincide with the central line of the thickness along width direction. So the bending moment and the hoop thrust of the lining could be derived using Equation 1 and Equation 2.

$$M = \frac{(\varepsilon_1 - \varepsilon_2)EI}{t} \tag{1}$$

$$N = \frac{(\varepsilon_1 - \varepsilon_2)EA}{2} \tag{2}$$

Where, ε_1 and ε_2 are the compression and extension strain measured during the model tests, E is the elastic modulus of the segment concrete, I is the moment of inertia of the segment, t is the thickness of the segment, A is the area and could be calculated by the thickness times the width of the segment.

The settlement of the tunnel was measured by the dial indicator at ring No. 5, No. 12, No. 19, No. 26, No. 33, No. 40, No. 46, so totally 7 settlement monitoring points were set along the tunnel. The settlement was measured at the crown of the tunnel. A settlement transmission device had to be designed because the tunnel model was embedded in the soil and its settlement could not be monitored directly. The transmission device contains a steel bar and a steel tube. The steel bar was used to transmit the settlement. One end of the steel bar was perpendicularly connected to the crown of the tunnel model and the dial indicator was put on the other end. The steel bar should be strong enough and not to deform during the settlement transmission. The steel bar was protected by the steel tube not to be affected by the surrounding soils.

3.2 *Procedure of the model test*

Two types of model tests were performed in terms of the permeability of the tunnel. One was finite permeable test, the other was impermeable test. In impermeable test, the tunnel joints were sealed by epoxy resin, while the tunnel joints were not sealed and kept as the original state in the finite permeable test. In both tests, the two ends of the tunnel were sealed to stop the inflow from the ends.

Figure 4. The water level measuring device.

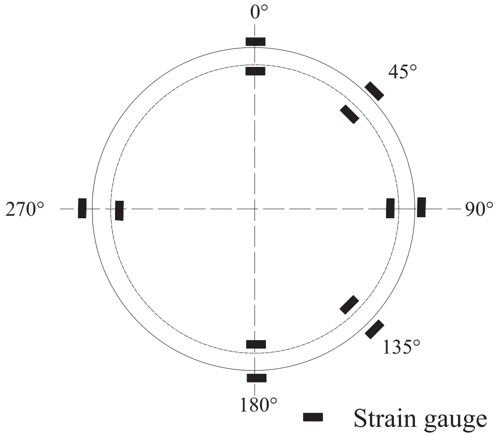

Figure 5. The distribution of stain gauges.

The sand was chosen as the soil medium in the model test to save testing time. The model test in the clay medium will be performed later. The permeability of the sand is larger than 10^{-5} m/s. The procedure of the tests is described in the following.

Step 1. The sand was laid layer upon layer in the steel container. The thickness of each layer was kept less than 5 cm to guarantee the density of the sand.

Step 2. The tunnel model was taken his place when the sand was laid until 48 cm thick from the bottom.

Step 3. The settlement transmission device was set on the crown of the tunnel perpendicularly.

Step 4. The sand was laid again over the tunnel with the same way as in step 1. The total thickness of the laid sand was 24 cm in this step.

Step 5. The verticality of the settlement transmission device was checked. Besides, it was ensured that the steel bar didn't nestle up to the steel tube.

Step 6. The dial indicators as well as data taker were finally installed.

The water was not recharged during both test, so the drawdown of water level was considered. The ongoing model test was shown in Figure 6.

Figure 6. The ongoing model test.

4 EXPERIMENTAL RESULTS AND ANALYSIS

4.1 *The development of tunnel settlement in finite impermeable test*

The evolution of tunnel settlements with time and water drawdown was shown in Figure 7–13. The water level was computed from the container bottom.

The initial water level in the test was 84 cm and the final water level was 63 cm. The tunnel leakage could be presented by the water level drawdown because the leakage from the tunnel joints was the only cause for water drawdown. The sand was used in the model test, so the tunnel leakage could be the main contribution to the tunnel settlement. The figures showed that the tunnel settlement is proportional to the water drawdown. The final settlements at Ring No. 5, Ring No. 12, Ring No. 19, Ring No. 26, Ring No. 33, Ring No. 40 and Ring No. 46 were 0.62 mm, 0.48 mm, 0.41 mm, 0.37 mm, 0.42 mm, 0.43 mm and 0.53 mm respectively. During the model test, more bubbles were found near the two ends of the tunnel model. This means that the leakage near the two ends was much more serious. Apparently, the leakage not only results in the tunnel settlement but also the differential settlement and in turn the differential settlement will accelerate the tunnel leakage. The differential settlement was shown in Figure 14. However, the relationship between the water level change and equivalent permeability of tunnel was not calculated.

4.2 *The development of tunnel settlement in impermeable test*

The tunnel joints were all sealed with epoxy resin to stop the water inflow. The typical tunnel settlements in the impermeable test were shown in Figure 15–21.

The behavior of tunnel under impermeable condition could be presented by Figure 15–21. Under impermeable condition, the tunnel experienced a certain heave at the beginning of the test due to the buoyancy produced when the water was injected into the test container. After about 30 hours, the heave of the tunnel reached the equilibrium and no settlement was developed thereafter because of the impermeability of the tunnel. It was found that the tunnel around Ring No. 46 exhibited a different behavior from the other parts of the tunnel. The settlement instead of heave was measured at Ring No. 46 because of the slight leakage there. The water level was not affected by the slight leakage around the Ring No. 46. The water level was kept as a constant during the model test.

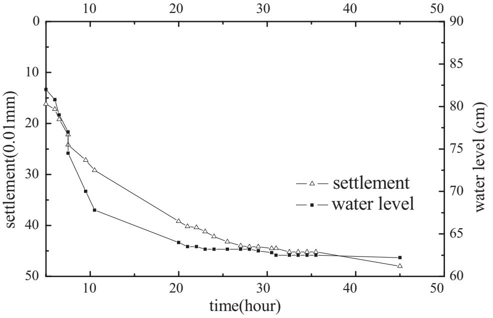

Figure 7. Development of tunnel settlement with time and water drawdown at Ring No. 5 in finite permeable test.

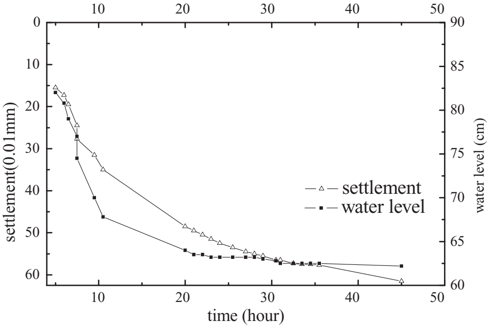

Figure 8. Development of tunnel settlement with time and water drawdown at Ring No. 12 in finite permeable test.

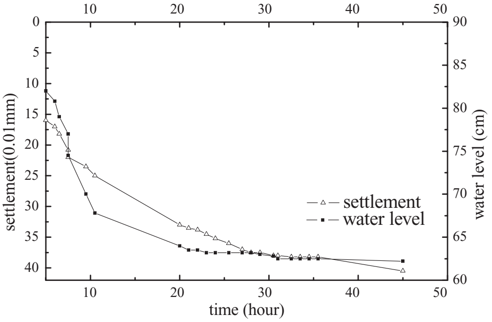

Figure 9. Development of tunnel settlement with time and water drawdown at Ring No. 19 in finite permeable test.

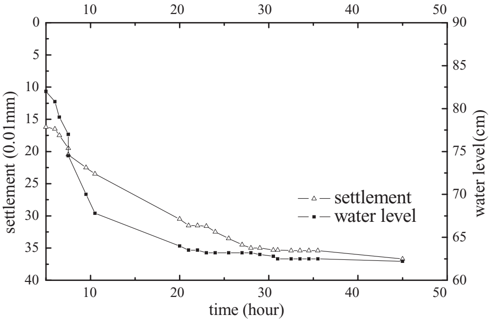

Figure 10. Development of tunnel settlement with time and water drawdown at Ring No. 26 in finite permeable test.

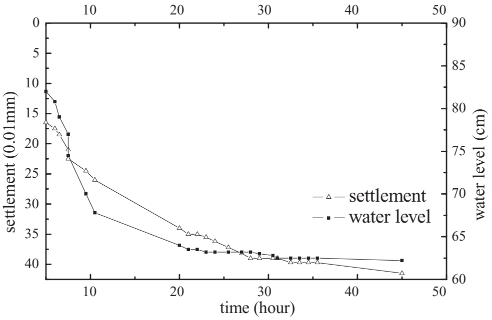

Figure 11. Development of tunnel settlement with time and water drawdown at Ring No. 33 in finite permeable test.

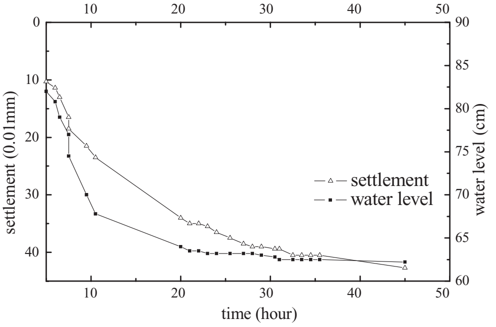

Figure 12. Development of tunnel settlement with time and water drawdown at Ring No. 40 in finite permeable test.

The influence of leakage on tunnel settlement could be revealed by the comparison on the evolutions of tunnel settlement under finite permeable and impermeable conditions. Improving the waterproof capacity of tunnel joints is an effective way to reduce the unfavorable influence of tunnel leakage.

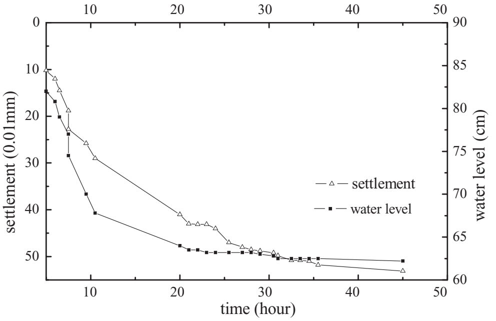

Figure 13. Development of tunnel settlement with time and water drawdown at Ring No. 46 in finite permeable test.

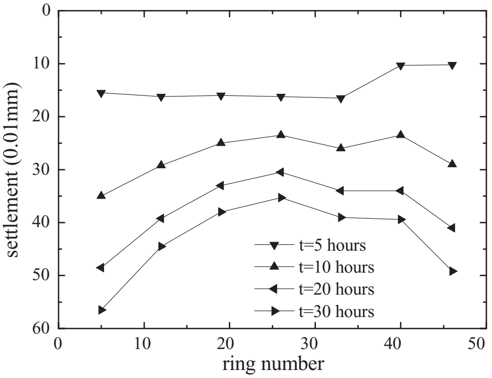

Figure 14. The differential settlement due to leakage in finite permeable test.

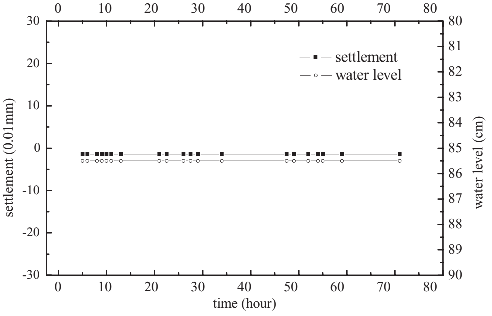

Figure 15. Development of tunnel settlement with time and water drawdown at Ring No. 5 in impermeable test.

4.3 *The development of lining moment in finite permeable test*

The moment of tunnel lining was obtained through the strain gauges and derived from Equation 1. The hoop thrust was not discussed in this paper considering its minor influence on the performance of tunnel lining. However, the strain gauges

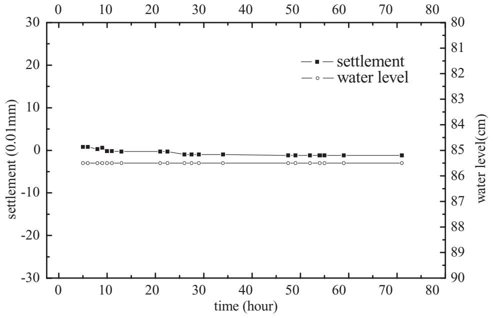

Figure 16. Development of tunnel settlement with time and water drawdown at Ring No. 12 in impermeable test.

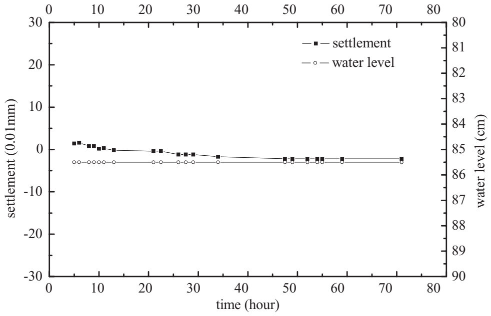

Figure 19. Development of tunnel settlement with time and water drawdown at Ring No. 33 in impermeable test.

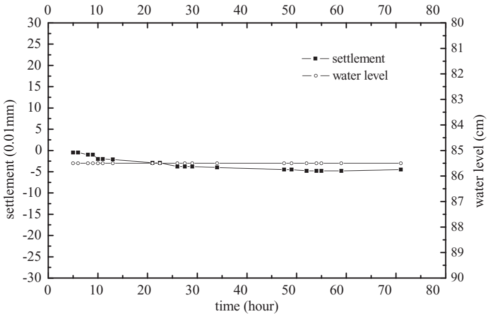

Figure 17. Development of tunnel settlement with time and water drawdown at Ring No. 19 in impermeable test.

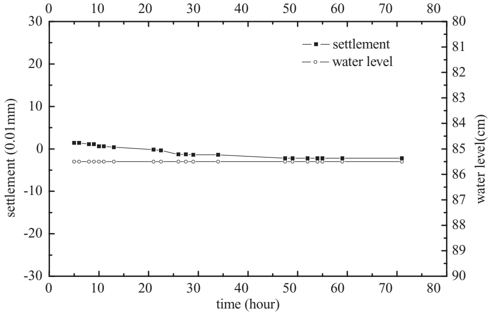

Figure 20. Development of tunnel settlement with time and water drawdown at Ring No. 40 in impermeable test.

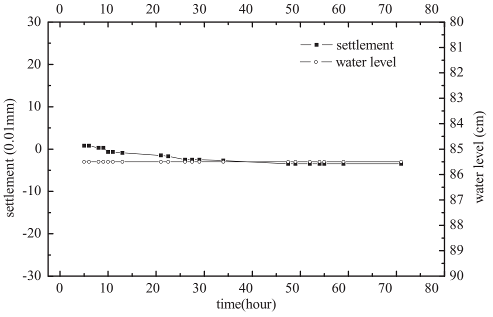

Figure 18. Development of tunnel settlement with time and water drawdown at Ring No. 26 in impermeable test.

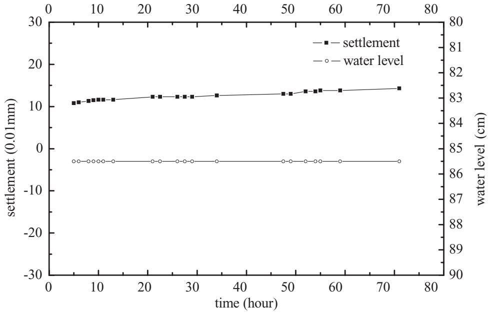

Figure 21. Development of tunnel settlement with time and water drawdown at Ring No. 46 in impermeable test.

at the positions of 45°,135° and 270° of the tunnel circumference were destroyed during the test. Therefore, the influence of tunnel leakage on the inner force of tunnel was presented by the variation of moment calculated at the position of 0°, 90° and 180° of tunnel circumference. The evolutions of the moment with time at Ring No. 26 and No. 37 were illustrated in Figure 22–23 respectively. The water level change could be referred in Figure 7–13.

Both Figure 22 and Figure 23 demonstrated that the tunnel leakage resulted in the significant increase of lining moment at tunnel crown and invert. However, the lining moment at the spring line did not change much. The moments at the crown and invert of Ring No. 26 increased from 47.1 N*mm to

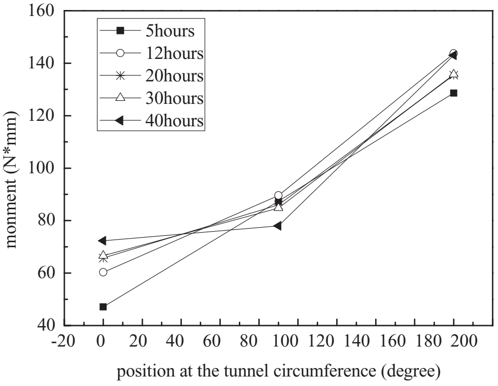

Figure 22. Variation of lining moment at Ring No. 26 in finite permeable test.

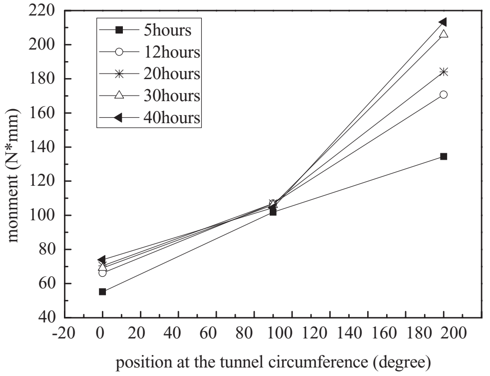

Figure 23. Variation of tunnel moment at Ring No. 37 in finite permeable test.

72.3 N*mm and from 128.6 N*mm to 143 N*mm when water level was dropped from 83 cm to 63 cm. More than 50% have been increased during the leakage period at the crown of the tunnel. While at Ring No. 37, the increase of moment at the tunnel invert is much more remarkable than that at the tunnel crown. The increase of lining moment at the tunnel crown and invert reached 34% and 59% respectively at Ring No. 37. Considering the measure errors during the test, it was hard to conclude the influence of tunnel leakage on the moment development at the tunnel crown and invert. However, one thing was clear that the tunnel leakage resulted in more increase of lining moment at the tunnel crown and invert rather than at the spring line of the tunnel.

Besides, it was found that the lining moment increase more quickly at the beginning of the test. The reason was the water level dropped quickly during this period and the water drawdown reached 18 cm, while the total drawdown of the water was 21 cm during the test. From this point of view, the variation of lining moment is proportional to the magnitude of drawdown of the water.

Additionally, the figures showed that the influence of tunnel leakage on the lining moment is more notable at Ring No. 37 than that at Ring No. 26. This could be explained when referring Figure 14 where the tunnel settlement was bigger at Ring No. 37 than that at Ring No. 26. This phenomenon revealed that the more serious the leakage, the more significant effect would have in terms of the tunnel settlement and lining moment.

4.4 *The development of lining moment in impermeable test*

The development of lining moment with time in impermeable test was presented in Figure 24–25.

Apparently, the lining moment in impermeable test did not change as much as that in finite

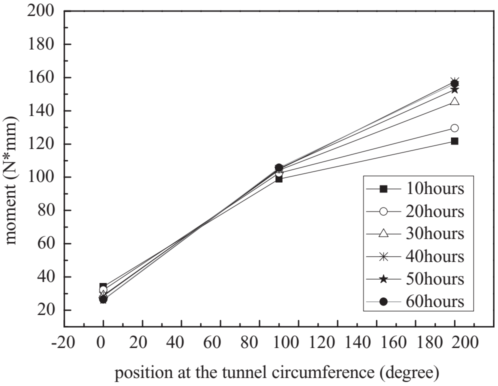

Figure 24. Variation of lining moment at Ring No. 26 in impermeable test.

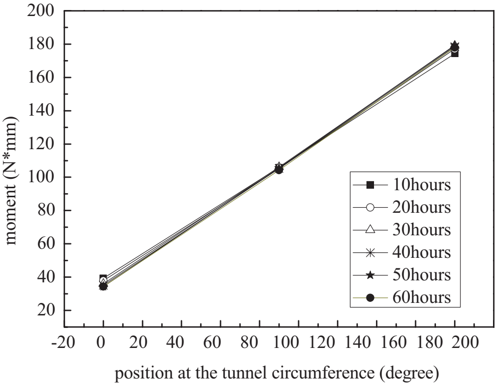

Figure 25. Variation of lining moment at Ring No. 37 in impermeable test.

permeable test. Theoretically, the inner force of tunnel lining should be kept as constant because the load exerted on the tunnel did not change at all during impermeable test. However, the moment at the tunnel invert of Ring No. 26 was scatted.

Although the lining moment did not increase under impermeable conditions, the lining moment at the spring line was higher in impermeable test than that in finite permeable test due to the larger buoyancy in former case.

5 CONCLUSIONS

Both finite permeable and impermeable small scale model tests were carried out with the prototype of Shanghai metro tunnel. The influence of tunnel leakage on the tunnel performance was studied in terms of the tunnel settlement and lining moment as well. The following was revealed from the tests:

a. The tunnel settlement increases continually with time when the tunnel lining is finite permeable. In contrast, the tunnel is lifted with time when the tunnel lining is fully impermeable and then reaches an equilibrium state. This is in accordance with the numerical modeling results of Mair (2008) where it was found that the long-term surface settlement increases with time when the tunnel is permeable and reduces with time when the tunnel is impermeable.
b. The tunnel leakage not only results in the tunnel settlement but also the longitudinal differential settlement. The longitudinal differential settlement leads to the opening of the circumferential joints of the tunnel. Consequently, it will accelerate the leakage of the tunnel. From this point of view, it is an effective way to improve the waterproof capacity of the tunnel joints to reduce the long-term settlement of tunnel and tunnel leakage as well.
c. The lining moments at the tunnel crown and invert increase with time when the tunnel is permeable. However, the variation of lining moment at the spring line of the tunnel could be ignored. The results from permeable test show that the more serious the tunnel leakage, the more increase of the lining moment at the tunnel crown and invert. In contrast, the lining moment does not have significant change all along the tunnel circumference. But the moment at the spring line is higher when tunnel is impermeable than that when tunnel is permeable.
d. The small scale model test is verified to be a useful way to study the behavior of tunnel with permeable and impermeable inflow regimes of tunnel lining. However, there is a big risk to monitor the inner force of the tunnel with strain gauges. Besides, the quantity of water inflow through each joint is difficult to measure and then it is not easy to build the quantitative relationship between tunnel leakage and settlement and inner force variation of the tunnel.

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