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Mechanical behavior of closely spaced tunnels – laboratory model tests and FEM analyses

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ABSTRACT: Reduced-scale model tests and corresponding finite-element analyses were performed to investigate the effect of different excavation sequences for twin tunnels under the unsymmetrical pressure in weak rock. In these tests, the alternative sequences of the excavation of the left tunnel first and then the right one, or the right first and then the left, were simulated. The displacement of ground and the earth pressure in the rock were measured. Particular attention was paid to the different behaviors of the displacements and the stresses caused by the different excavation sequences. The result of the present study indicates that the state of stresses, the displacements around the tunnels and the ground surface settlements are all different when the excavation sequence is alternated. When the right one is excavated firstly, the stratum condition is more deteriorated. It can be concluded that the sequence of the left first and then the right one is better for such twin tunnels.

1 INTRODUCTION

With the development and the upgrade of infrastructures such as highway, subway, railway, and many other facilities, tunnel constructions are gradually increasing in the recent years. The preference in China, and as well as in other countries, is to use twin tunnels for the new transportation lines rather than a single larger diameter tunnels, when the space is limited.

Model test and numerical simulation are two key methods to investigate the tunneling problems. In the past two decades, the rapid advances have been made in tunnel model tests, many of which are investigations on the twin tunnels. Dhar et al. (1981) performed the fracture pattern around twin openings in weak materials of sand wax and sand wax mixtures with the plaster of Paris under controlled loading conditions. Twin openings for different orientations in respect to loading directions were studied. Adachi et al. (1993) also used model tests to analysis the interaction between twin tunnels. The tunnel excavation was simulated by tailor-made diameter reducible device. Chu et al. (2006) performed model tests of twin circular tunnels in homogenous material, two-layered formations, and three-layered formations to understand the mechanical behavior of a twin-tunnel of circular cross section in multi-layered formations, and a two-dimensional numerical simulation was also developed.

Using 2D and 3D numerical simulations, Ghaboussi (1977), Soliman (1993), Addenbrooke (1997), Ng (2004) et al. investigated some aspects of interaction mechanisms.

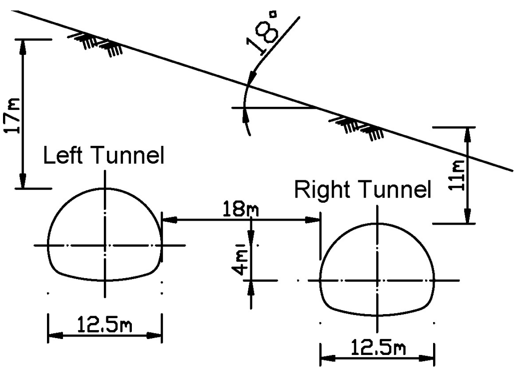

Figure 1. Typical cross section of Pingnian Tunnel.

Pingnian Tunnel is a typical twin-tunnel, which was constructed in accordance with the principles of the New Austrian Tunneling Method in weak rock, being part of Luofu expressway in Yunnan Province. Tunnel width is 12.5 m, and the length is about 360 m. Spacing between two tunnels changes from 18 m (at Luochunkou site) to 25 m (at Funing site). The tunnels are under the inclined ground surface and the two tunnels are not constructed in the same level, and the vertical distance between them is from 3 m to 4 m. The typical cross section is shown in figure 1.

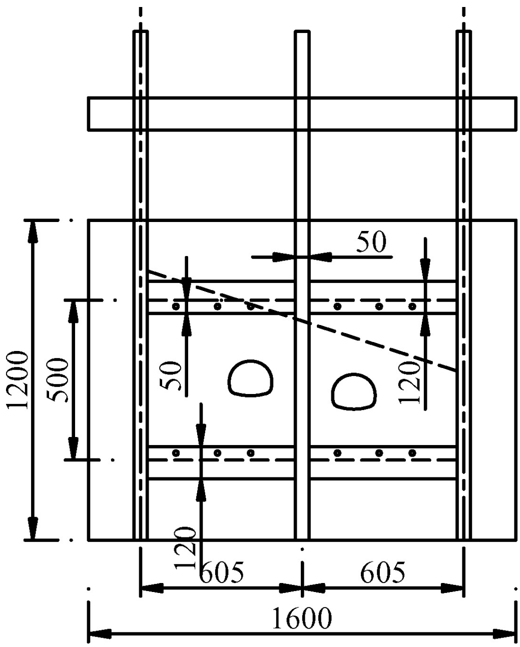

Figure 2. Sketch of steel frame with model tunnel (Unit: mm).

So far, the behavior of surrounding ground during the single tunnel excavation has been extensively investigated, however, the case that a tunnel is driven paralleling to another adjacent tunnel is of interest to tunnel engineers. During the Pingnian Tunnel construction, a collapse happened at the left line portal, and the slip also affected the adjacent portal of right line because of the small space between the two tunnels. In order to study the actual interaction between two tunnels, two-dimensional laboratory model tests were performed to capture the earth pressure transfer and the displacement of surrounding rock during construction. The particular attention was paid to the evolution of the displacements and stresses caused by the different excavation sequence. The numerical simulations by the FEM were also conducted for the problem to compare the analytical results by model tests.

2 SIMULATION METHODS

2.1 *Two-dimensional plane strain test*

Although actual tunneling is a three dimensional problem and actual ground is heterogeneous as well as anisotropy in nature, in this study, plane strain tests were conducted in a homogeneous ground by simplification. The box used in tests was made of a steel frame, as shown in figure 2, with dimensions of 1.6 m × 1.2 m × 0.4 m. The four sidewalls of the test box were assembled using steel sheets. For the case of the observation of the ground movement patterns during testing, two transparent Perspex plates were used at the front and back sides.

Table 1. Properties of the ground material for the model tests.

Unit weight γ (KN/m^3)	26.9
Young's Modulus E (MPa)	38
Cohesion c (KPa)	25
Friction angle φ (deg)	39

The tests were conducted according to the typical cross section in the steel frame as shown in figure 2. The tunnel width is 156 mm, the horizontal distance between two tunnels is 225 mm, the vertical distance is 500 mm under inclined ground with angle 18°, and the cover depths of left and right tunnel are 212 mm and 138 mm respectively. All dimensions are controlled by the geometrical similarity ratio of 1/80.

The ground material used in the model test was composed of barite powder, sand and plaster mixed with water, and the quality proportion was achieved through a series of material tests. The main parameters of the ground material are shown in table 1, determined by the following expressions according to the similarity theory.

$$C_\varphi = 1, \tag{1}$$

$$C_\gamma = 1, \tag{2}$$

$$C_\sigma = C_E = C_c, \tag{3}$$

$$C_\sigma = C_\gamma \cdot C_l = C_l = 80, \tag{4}$$

where $C_\varphi, C_\gamma, C_\sigma, C_E, C_c, C_l$ are the similarity ratios for friction angle φ, stress σ, young's modulus E, cohesion c, unit weight γ and geometrical dimension l, which represent relationship for the parameters between the model test and the real situation.

The excavation was simulated by removing the ground inside the excavation zones manually, with the two different excavation sequences conducted: the left tunnel excavated first and then the right one (named test A), and the right first and then the left (named test B). A monitoring program was utilized to record the process of the ground movements and the earth pressure changes around the tunnels. Monitoring items included earth pressure cells, deep rods and micrometer gauges, and the locations of items shown in figure 3 and figure 4. All monitoring items were attached to the high-speed instrument of static strain gauge (YE2539), collecting data at any interval operator set.

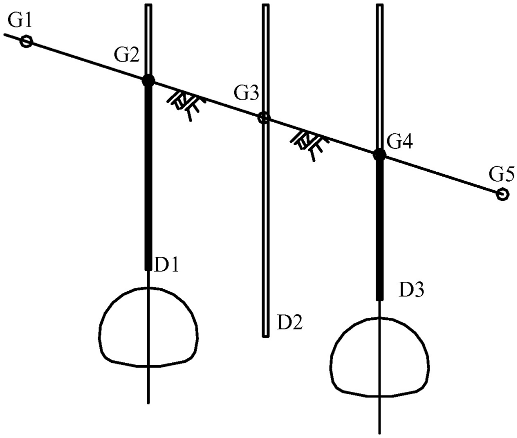

Figure 3. Locations for displacement gauges.

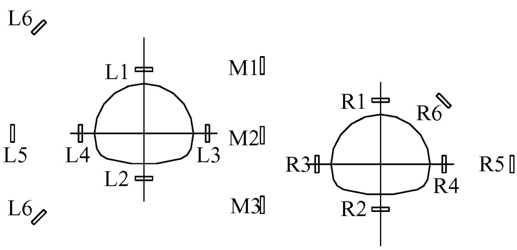

Figure 4. Locations for earth pressure gauges.

2.2 *Numerical simulation*

Corresponding numerical simulation was performed to compare the above experimental tests. The simulations were based on the model test conditions and the material properties. The finite element software Msc.Marc was adopted for the simulations. In the analyses, the ground material was assumed to be elastic-plastic confirming to the Druker-Prager failure criterion together with the associated flow rule. The analysis consisted of two phases: the first phrase is to create an initial geostatic condition and the second phase to simulate the excavation process. During the first phase, the initial geostatic condition was achieved by applying gravity forces to all ground elements. In the second phase, the excavation process was simulated by removing the elements inside the excavation zone. The simulation of the test A and the test B performed in laboratory model tests were conducted accordingly.

3 RESULTS

3.1 *Displacement*

Figure 5 is a surface displacement-time diagram, which is obtained in the model test. From the figure we

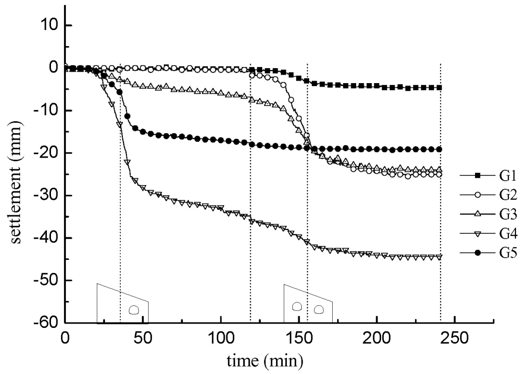

Figure 5. Surface settlement curves (obtained in model test).

can find that the settlement of every test point increases step by step along with the advancement of excavation. A substantial increase of the displacement occurs when excavation section passes the test section. The settlement develops continuously after excavation finished and reaches the steady-state in a period of time. The creep displacement is the major part during the period of the excavation termination, accounting for about 10%~30% of the total displacement.

There is still some ground surface settlement (at G2, G4) increasing during the excavation process of adjacent tunnel, which reveals the existence of an interaction between the twin tunnels. G1 located above and left to G2, whose horizontal distance to the left wall of the left tunnel is one time of width of the tunnel, doesn't undergo a distinct displacement during the excavation of the right tunnel while it does during the excavation of the left one. The displacement of the lower G5, located in the right to the G4, is totally different, which is mainly affected by the excavation of right tunnel. For the spot G3, located at the surface above the pillar centerline, the settlement is still in the development state and the excavation of both the right and the left tunnels will produce effect on it; the two abrupt changes of the displacement happened in the excavation section passing the test one. The displacement change of the spot G3 appears smaller than the displacement of the spot G2 and G4.

We can make a conclusion from the above: the influence of tunnel excavation decreases with the increase of the distance to the excavated tunnel. The zone influenced mostly is those above the tunnels. Under such leaning stratum, the influence of the excavation to rocks in one time of the width of the tunnel region still exists, but it is small when the distance between the tunnel and the rock is more than three times of the width of the tunnel. Excavations of left and right tunnel all have effect on surface above the pillar.

The comparison between deep settlement (settlement of the inner stratum, indicated by D1, D2 and D3,

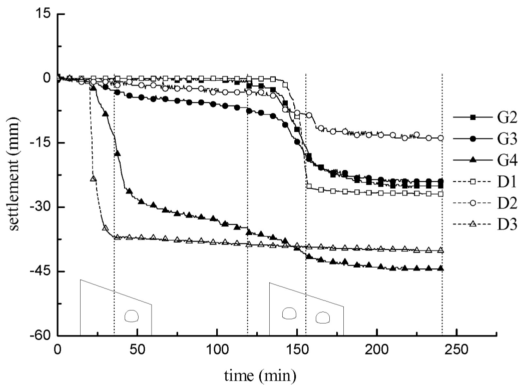

Figure 6. Surface and deep ground displacement curves (obtained in model test).

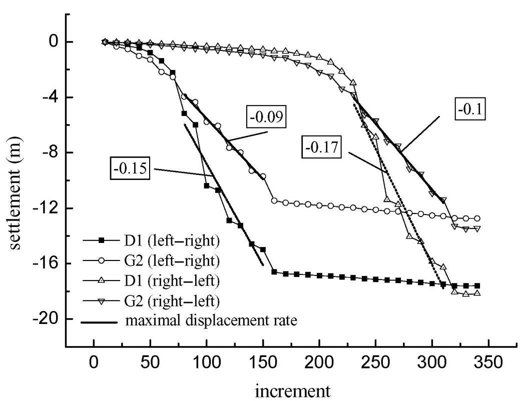

Figure 7. Surface and deep ground displacement curves (obtained in FEM analyses).

located above the left tunnel crown, in the pillar center line parallel to the right tunnel spring line and above the right tunnel crown respectively) and corresponding surface settlement is shown in figure 6. The development trends are coincident, however, deep settlement occurs prior to that of the surface, and its displacement rate is also relatively bigger. Time to steady state needed by the deep displacement is shorter than that of the surface settlement. When it comes to compare two tunnels, the displacement rate of the left tunnel is bigger than the right one.

In the test A, settlements of all measure points are more than those got in the test B. The maximal displacement is 35.9 mm when the left tunnel excavated first and then the right one, and it is 44.4 mm when the right one first and then the left. So it indicates that the left tunnel excavated first can control surface displacement more effectively. The comparison of surface settlements between two opposite construction sequences achieved in numerical simulations are

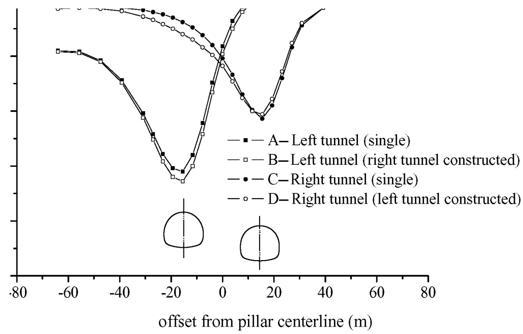

Figure 8. Transverse settlement trough corresponding to different excavation sequences (obtained in FEM analyses).

shown in figure 7. It reaches the same conclusion that the ultimate surface settlement occurred by the right tunnel excavated first is bigger than that occurred in the reverse excavation sequence. The evolution law of the displacement rate is the same of the settlement. So it is not beneficial for the tunnel stabilization to adopt the construction sequence with the right tunnel excavated before the left tunnel under such locations as the Pingnian twin tunnel under the inclined stratum.

The whole surface settlement curves can be obtained through FEM analyses, shown in figure 8. Based on these curves it can be concluded that, with the right tunnel finished, the excavation of the left tunnel (the curve B in figure 8) will generate more displacement than that caused by the excavation in green field (the curve A in figure 8). The disturbance due to the right tunnel construction lowers the stiffness of the rock around the left tunnel and when the left is constructed, the rock in the previously disturbed zone is disturbed again, and it will move more than what is expected. So, the existing of the right tunnel is undesirable for the left one. However, when there is the adjacent tunnel existing, additional ground surface settlement caused by right tunnel excavated (the curve D in figure 8) is less than that caused in green field (the curve C in figure 8). The existing of the left tunnel which is higher than the right one is an advantage for the right tunnel to a certain extent.

3.2 *Earth pressure*

Earth pressure near the crown and the invert (R1 is above the crown and R2 is under the invert, refer to figure 4) of the right tunnel are given in figure 9. There is the same development rule for the earth pressure of R1 and R2; the pressure increase a bit due to the previous tunnel excavation, and decrease rapidly as excavation section passes the test section because of the load release caused by removing rock of the tunnel space.

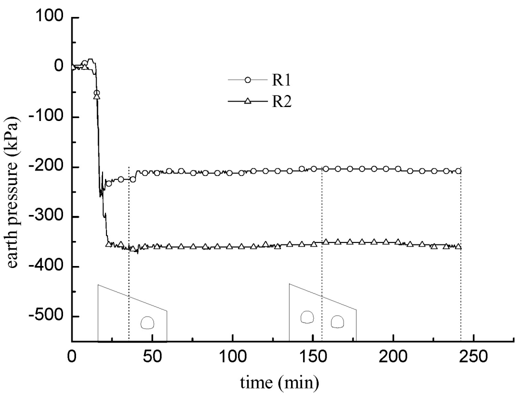

Figure 9. Earth pressure near crown and invert of right tunnel (obtained in model test).

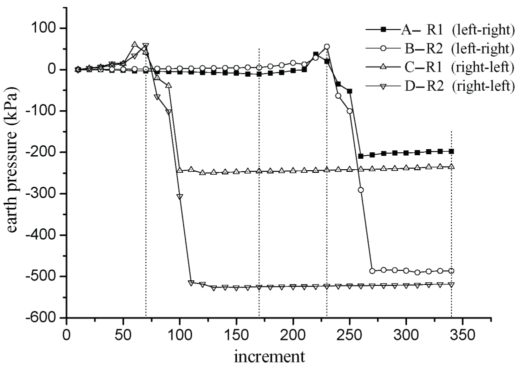

Figure 10. Earth pressure at crown and invert of the right tunnel.

The pressure change at R2 near the crown is bigger than that at R1 near the invert. The phenomena should be associated with the locations of two measuring points, the invert is deeper than the crown and initial stress near the invert is bigger than that near the crown. The same conclusion can be drawn by numerical simulation and the results are shown in figure 10. The stress changes caused by the excavation of the right tunnel in green field are more than that caused with the existing left tunnel. And it comes to opposite conclusion for the left tunnel. So, depending on the stress changes, the same conclusion can be drawn: the existing of the right tunnel is undesirable for the left one; and the existing left tunnel is beneficial to the right one.

4 CONCLUSION

The reduced-scale laboratory tests and their corresponding numerical analyses were performed to investigate the transfer of the earth pressure and the displacement of the surrounding rock during the construction. At the same time the effect of different excavation sequences was analyzed.

The degree of the interaction between the two tunnels is proportional to the distance between them. The changes of stresses and displacements of the rocks along the tunnel are mainly affected by its excavation while the effect caused by the adjacent tunnel is small. The interaction effects on the two tunnels are different: the existing of the right tunnel deteriorates the properties of rocks around the left tunnel, which is harmful to the left tunnel; whereas the existing left tunnel reduces the asymmetric degree, and therefore benefits to the right tunnel.

Stress decreases rapidly with the excavation of the tunnel, which causes settlements of the surrounding rocks and consequently expands to surface.

Displacements of the rock increase gradually along with the excavation advancement, and the main portion occurs when the excavation section passes the test section. After the excavation finished, a creep displacement takes place, which accounts for about 10%∼30% of the total displacement.

The difference of the excavation sequence causes the different development rule of the stress field and the displacement field. The values of displacements and stresses increase on adopting right tunnel excavated firstly. For the tunnels like the Pingnian tunnel, which is a shallow tunnel under unsymmetrical pressure with the vertical distance between the tunnels, it is profitable to excavate the left tunnel firstly.

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