Model Test on Ground Surface Settlement and Face Failure of Shallow Tunnel in Dry Sandy Stratum

Weitao Song¹; Pei Zhang².³*; Xiuli Du¹

¹ Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing, 100124, China
² School of Civil and Transportation Engineering, Beijing University of Civil Engineering and Architecture, Beijing, 102616, China
³ Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, 999077, China

First author’s e-mail: songweitao@emails.bjut.edu.cn
*Corresponding author’s e-mail: zhangpei@bucea.edu.cn

Abstract. Surface deformation and face failure may occur during shield tunneling in the shallow buried dry sandy stratum. The model shield machine is used to carry out the shield tunneling model test in dry sandy stratum. The surface deformation laws and the active failure process of the excavation face are analyzed by monitoring the surface deformation during advancing and face failure stages. It is concluded that the surface deformation curve is “M” shaped and asymmetrical about the tunnel axis. The surface settlement during face failure goes through two stages, and the surface collapse pit is approximately elliptical, whose center is located on the left side of the tunnel axis when the cutter head rotates clockwise.

1. Introduction

Dry sandy stratum is a common engineering geological body, which is widely distributed all over the world. Excessive surface deformation may occur owing to the characteristics of looseness and non-cohesive. Meanwhile, the surface settlement and even collapse may occur if the support pressure in the shield chamber is too small[1-3]. Therefore, it is of great significance to research the surface deformation and face failure during shield tunneling in dry sandy stratum.

Much research has been conducted on the surface deformation laws during shield tunneling in dry sandy stratum. Theoretical analysis method proposed calculation formulas for ground deformation by introducing the related theory of rock and soil mechanics disciplines into the research of ground deformation[4-6]. The Peck formula[7] is the most widely used method to describe the characteristics of surface settlement[8, 9] among the existing empirical methods. In the study of model test, Sohaei et al.[10] conducted a ground movement experiment by pulling out the pipe casing tunnel shield progressively and replacing it with an elastic aluminum tunnel liner in the model box, results show that the transverse surface settlement troughs obtained by physical modeling can be well described by the Peck formula, and remarkable deformation on the ground surface will occur in shallow and loose sandy stratum during tunneling. Fang et al.[11] used a model shield machine with a diameter of 520mm to carry out the shield tunneling model test in sandy soil and obtained the same conclusion. Fang et al.[12] divided the surface settlement-time history curve into four stages based on the model
test results. Besides, shield tunneling parameters, such as advancing speed, grouting volume, etc., are important factors that affect the surface settlement[11, 13, 14]. Overall, much research has been carried out to study the laws of surface settlement, however, little research has conducted on the surface deformation laws and the change of the soil pressure in shield chamber by reducing the tunneling parameters in the model test, especially reducing the speed of discharging soil.

Some scholars have carried out much research on the active failure process in dry sandy stratum. In the research of numerical simulation, most numerical calculation models[15-17], including the resemble shield advancing and rotating model[1, 18], are built to study the limit support pressure and failure mode of excavation face. In the research of model tests, the commonly used methods to achieve the active failure are stress control method[19, 20] and displacement control method[2, 21]. Chen et al.[2] used a self-designed displacement control equipment to conduct the face failure model test in dry sandy stratum, concluded that the surface settlement has experienced no obvious stage and significant increase stage with the retreat distance of the supporting plate, and the surface collapse pit is 1D width and 0.75D long. Sun et al.[3] obtained a funnel formed surface collapse pit using displacement control model test equipment. Thorpe et al.[20] and Idinger et al.[21] obtained similar surface collapse pit. In summary, much research focused on the limit support pressure and failure mode of the shield excavation face, however, the development process of the surface collapse and the shape and location of the surface collapse pit are rarely studied. Meanwhile, the method of discharging soil and rotating the cutter head is rarely used to attain the face failure process in the existing research.

To study the surface deformation laws and the active failure process of the excavation face during shield tunneling in shallow buried dry sandy stratum, the shield tunneling model test is carried out using the designed model shield tunneling machine. The surface deformation laws during tunneling and the active failure process of the excavation face are analyzed.

2. Model test design

2.1. Model test platform

For studying the laws of surface deformation and face failure process during shield tunneling in dry sandy stratum, our research group independently designed and developed a shield tunnel excavation model test platform[22], mainly composed of model box, model shield machine and control system. The model test platform is shown in Figure 1.

The model box is a rigid box, whose size is 2.0m×2.0m×1.5m (length × width × height). There are two holes with a diameter of 285mm on the front and back walls of the box, and a partition can be placed inside the model box to divide the model box into two independent spaces. The model shield machine is a top-in advancing device, the shield shell and the lining are connected together advancing with the cutter head. It can attain the functions of shield advancing, cutter head cutting and discharging soil. The diameter of the shield lining is 280 mm, and the excavation diameter is 285 mm, which is equivalent to 4% deformation loss. The opening ratio of the cutter head is 45%, and the maximum discharge particle size of the screw conveyor is 10 mm. Besides, the control system can monitor and adjust the tunneling parameters, such as the advancing speed and the rotating speed of the cutter head, during the whole tunneling process.
2.2. Dry sandy stratum

In the model test, dry silt sand with a particle size ranging from 0.15mm to 0.25mm is used as the stratum material. The degree of compaction of the stratum in the model test is designed as medium density. Based on the maximum dry density and minimum dry density measured in the indoor relative density test, the relative density $D_r$ of the stratum is taken as 0.55, and thus the density of the stratum in the test is calculated to be 1525 kg/m³, as shown in Table 1.

| Dry sandy stratum density | Minimum dry density | Maximum dry density | $D_r=55\%$ |
|---------------------------|---------------------|---------------------|------------|
| Density (kg/m³)           | 1334                | 1728                | 1525       |

The moisture content test and direct shear test are carried out for the dry sand in the model test. Results show that the moisture content of the dry sand is approximately zero, and the internal friction angle is 36°. Besides, the buried depth of the sandy stratum in the model test is designed to be $1D$, and $D$ is the diameter of the tunnel.

2.3. Tunneling plan

The model test aims to study the laws of surface deformation during shield tunneling and the active failure process of the excavation face for the dry sandy stratum. The model test in this paper is carried out in half of the model box. The tunneling plan of the model test was formulated, and two stages are divided in the model test, shown in Figure 2. In the following description and analysis, the center of the cutter head panel is the origin $o$, the tunneling direction is the positive direction of the $y$ coordinate, and the right side of the tunneling direction is the positive direction of the $x$ coordinate.
At the advancing stage, the model shield machine advances from \( y_0 \) to \( y_{400} \), aiming to research the surface deformation laws. The advancing speed is set to be 5 mm/min, the rotating speed of the cutter head is 1 r/min, and the initial rotating speed of the screw conveyor is 5 r/min at the beginning. Both the rotating speed of the cutter head and the advancing speed remain unchanged, however, the rotating speed of the screw conveyor is changed, as shown in Figure 3.

![Figure 3. The rotating speed of screw conveyor with advancing distance](image)

At the face failure stage, the model shield machine stops at \( y=400\)mm. This stage aims to study the active failure process of the excavation face. The face failure process is achieved by adopting the method of cutter head rotating and soil discharging. The rotating speed of the cutter head is 0.2 r/min, and the rotating speed of the screw conveyor is 1 r/min during the face failure process. The discharged soil is weighted every 15s, and the test stops at 48 minutes.

2.4. Monitoring points layout

Based on the purpose and tunneling plan of the model test, the corresponding monitoring points are arranged in the model box. The layout of the monitoring points for the two stages is shown in Figure 4. For the advancing stage, the surface deformation during shield tunneling is monitored, the monitoring sections are \( y_{190} \), and the number of the monitoring points ranges from 1 to 10 in Figure 4. For the face failure stage, the process of face failure and surface collapse is monitored, the monitoring section is \( y_{470} \) and \( x_0 \), the number of monitoring points ranges from 11 to 22 in Figure 4.
Figure 4. The layout of the surface monitoring points

The surface deformation is measured by a rod displacement gauge, which is fixed by the surface displacement monitoring devices, as shown in Figure 5. While fixing the rod displacement gauge, the fixed bracket composed of different lengths of steel pipes above and around the model box is installed firstly to form a fixed whole with the model box, as shown in Figure 5(a). Then, the rod displacement gauges are fixed on the fixed bracket with a “7”-shaped steel plate, as shown in Figure 5(b). At last, a small steel sheet with a side length of 20mm is pasted under the rod displacement gauge to prevent it from inserting into the ground, as shown in Figure 5(c).

Figure 5. Surface displacement monitoring device: (a) installing fixed brackets, (b) fixing the surface displacement gauge and (c) paste a steel sheet

2.5. Filling plan

The test is carried out in half of the model box with a bottom area of 2.0 m×1.0 m. The density control method is adopted during filling, that is to say, the same weight of the soil is filled with for each layer. The control height for each layer is 10 cm, and the weight is 305 kg based on the density of the soil. The compaction method is manual compaction with a rammer.

Figure 6 presents the filling soil process in the model test. Firstly, pouring the soil into the model box by region with a plastic bucket many times until the soil weight is 305 kg. Then, flattening the soil with a flat board and tamping it with a rammer until it reaches the target height of this layer. Next, checking the target height and flatness of the soil using an infrared level instrument. If the height is not reached, continue tamping to the target height. Instead, loosening the soil and ret-tamping this layer. Finally, filling to the surface by layer according to the above filling methods.
3. Test results in the advancing stage

The surface deformation on the y190 section is monitored during the advancing stage, and the distance-history curve of surface deformation and the shape of the transverse surface deformation trough are analyzed.

3.1. The distance-history curve of surface deformation

The distance-history curve of the surface deformation for the y190 monitoring section during the advancing stage is shown in Figure 7. It describes that the surface deformation is very little when the advancing distance is within 60 mm, and then it increases rapidly to the maximum when advancing distance ranges from y120 to y140. After that, some curves gradually stabilize after a falling stage, however, other curves remain stable without the falling stage.

From Figure 7, we can see that the advancing locations where the surface deformation starts to increase and reaches the maximum in the curves correspond to the curves between the screw conveyor rotating speed and advancing distance in Figure 3. Surface uplift occurs when the rotating speed of the screw conveyor decreases to 4 r/min at y50 in Figure 3, and the surface uplift value reaches the maximum when the rotating speed of the screw conveyor will return to 5 r/min between y120 and y130. It is proved that the tunneling parameters, e.g. the rotating speed of the screw conveyor, have a significant and direct effect on the surface deformation of the shallow buried dry sandy stratum.

The curves of surface deformation and advancing distance for points 3 to 8 have descending stage after advancing distance of 120 mm, while the points 1, 2, 9 and 10 don’t have. The reason is that the range of surface uplift caused by the decrease of the rotating speed of the screw conveyor is bigger than that of the surface settlement caused by normal excavation speed. It can be interpreted as “the scope of passive failure of excavation face is greater than that of active failure” [23, 24]. After advancing to y120mm, the regions where the surface deformation decrease is between points 3 to 8, corresponding to x=-280mm to x=210mm.

![Figure 7. The distance-history curve of surface deformation for the y190 section](image-url)
Meanwhile, the earth pressure increment on the shield chamber board is monitored, as shown in Figure 8. It can be seen that the earth pressure increment remains unchanged at first and then increases and decreases later, it remains relatively stable at last. Comparing the curve of the rotating speed of the screw conveyor and the advancing distance in Figure 3, we can find that the variation laws of earth pressure increment in Figure 8 are similar to that of the rotating speed of the screw conveyor. Besides, the earth pressure increment changes with the change of the rotating speed of the screw conveyor, keeping simultaneity and no hysteresis. Therefore, the rationality of tunneling parameters can be judged by monitoring the change of earth pressure in the shield chamber.

3.2. Transverse surface deformation laws

The surface deformation curve of each monitoring point on the y190 section for different advancing distances is shown in Figure 9. It shows that the transverse surface deformation curve is “M” shaped, which is different from the Gaussian form described by the Peck formula when tunneling from y120 to y400. The deformation maximum is located at x=-280mm and x=110mm, and the surface deformation value above the central axis of the tunnel is very small.

From Figure 3, we know that the advancing range where the rotating speed of the screw conveyor is less than 5 mm/min is from y50 to y125, and it keeps 5 mm/min at other advancing ranges. Therefore, the surface deformation at y120mm is the biggest, and it decreases after y120mm in Figure 9. It proves that the surface deformation in the shallow buried dry sandy stratum is directly controlled by the tunneling parameters, e.g. ration speed of the screw conveyor. Besides, the surface deformation values are distributed asymmetrically about the tunnel central axis due to the influence of cutter head rotating disturbance.

![Figure 8. Variation laws of the earth pressure increment on the chamber with the advancing distance](image8)

![Figure 9. Transverse surface deformation curves](image9)
4. Test results in the face failure stage
After the shield reaches 400 mm, the model test stops for six hours. Then, the active face failure stage starts by the method of discharging soil and cutter head rotating. The development process of the face failure is reflected and analyzed by monitoring the discharged soil weight and the surface settlement.

![Graph showing variation laws of discharged soil weight](image)

**Figure 10. Variation laws of the discharged soil weight with time**

**4.1. Discharged soil weight**
The variation laws of the discharged soil weight every 15s and the total discharged soil weight with time are recorded during the face failure process, shown in Figure 10. It shows that the curve of the total discharged soil weight with time is approximately a straight line, indicating that the discharged soil weight is stable, which ensures the continuity of the active failure process. Besides, the discharged soil weight every 15s ranges from 15g to 35g, floating up and down in a wave style.

**4.2. Development process of face failure**
In the process of face failure achieved by the method of discharging soil, the soil particles in front of the cutter head enter the chamber continuously through the opening of the cutter head while the soil in the chamber is discharged. The time-history curve of the surface deformation of the measuring points during face failure is shown in Figure 11.

![Graph showing surface settlement time-history curve](image)

**Figure 11. Surface settlement time-history curve**

Figure 11 shows that only measuring point 11 has obvious settlement change, the settlement changes for other measuring points are very small. For point 11, the surface settlement curve with time can be divided into two stages: no obvious settlement stage and rapid increase stage. The time when the screw conveyor starts to discharge soil is 0 min, and the obvious settlement value appears at 30
min, which shows that the influence of face failure lags to ground surface due to the soil arching effect. Besides, the scope of surface settlement is mainly the limited area directly above the cutter head.

![Figure 12. Surface collapse pit: (a) Location of the collapse pit and (b) Partially enlarged figure](image)

In the face failure stage, the surface collapse pit has experienced a development process from nothingness to being and from little to large. The shape and location of the surface collapse pit after the test are shown in Figure 12. It can be seen that the center of the surface collapse pit is not on the longitudinal axis of the tunnel, but on the left side of the tunnel axis in the direction of shield tunneling, which is caused by the rotating disturbance of the cutter head.

Meanwhile, the outline of the surface collapse pit is elliptical and the length perpendicular to the tunneling direction is greater than that of the width in the tunneling direction by observing the outline of the surface collapse pit. Besides, the center of the collapse pit on the left side of the tunnel axis when the rotating direction of the cutter head is clockwise.

5. Conclusion

The shield tunneling model test was carried out to explore the laws of surface deformation and the active failure process of the excavation face in the shallow buried dry sandy stratum. The main conclusions are as follows:

1) The tunneling parameters, e.g. the rotating speed of the screw conveyor, have a significant and direct effect on the surface deformation of the shallow buried dry sandy stratum. The earth pressure in shield chamber changes with the rotating speed of the screw conveyor simultaneity.

2) The transverse surface deformation curve caused by shield tunneling in the shallow buried sandy stratum is “M” shaped, which is closely related to the shield tunneling parameters. The transverse surface deformation is distributed asymmetrically about the central axis of the tunnel due to the influence of the cutter head rotating.

3) The discharged soil weight increases uniformly with time during face failure. The surface settlement has gone through two stages: no obvious settlement and rapidly increasing settlement. The surface collapse pit is approximately elliptical, and the center of the collapse pit is located on the left side of the central axis of the tunnel when the rotating direction of the cutter head is clockwise.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (52025084, 51908023), the China Postdoctoral Science Foundation (2019 M650465), the Beijing Postdoctoral Research Foundation (2019-PC4) and the Pyramid Talent Training Project of Beijing University of Civil Engineering and Architecture. This support is gratefully acknowledged.

References

[1] Wang J, He C, Xu G. (2019) Face Stability Analysis of EPB Shield Tunnels in Dry Granular Soils Considering Dynamic Excavation Process. Journal of Geotechnical and Geoenvironmental Engineering, 145: 0401909211
[2] Chen R, Li J, Kong L, et al. (2013) Experimental study on face instability of shield tunnel in sand. Tunnelling and Underground Space Technology, 33: 12-21.

[3] Sun X, Miao L, Lin H, et al. (2018) Soil Arch Effect Analysis of Shield Tunnel in Dry Sandy Ground. International Journal of Geomechanics, 18(6): 04018057.1-04018057.15

[4] Sagaseta C. (1987) Analysis of undrained soil deformation due to ground loss. Géotechnique, 37(3): 301-320.

[5] Verruijt A, Booker J R. (1998) Surface settlements due to deformation of a tunnel in an elastic half plane. Géotechnique, 46(4): 753-756.

[6] Lu D, Kong F, Du X, et al. (2019) A unified displacement function to analytically predict ground deformation of shallow tunnel. Tunnelling and Underground Space Technology, 88:129-143.

[7] Peck R. (1969) Deep Excavations and Tunneling in Soft Ground. Proc. of 7th ICSMFE, Mexico.

[8] Attewell P, Yeates J, Selby A R. (1986) Soil Movements Induced by Tunnelling and their Effects on Pipelines and Structures. Methuen inc new york ny.

[9] Migliazza M, Chiordoli M, Giani G P. (2009) Comparison of analytical method, 3D finite element model with experimental subsidence measurements resulting from the extension of the Milan underground. Computers and Geotechnics, 36(1-2): 113-124.

[10] Sohaei H, Hajihassani M, Namazi E, et al. (2020) Experimental study of surface failure induced by tunnel construction in sand. Engineering Failure Analysis, 118:104897.

[11] Fang Y, He C, Nazem A, et al. (2017) Surface settlement prediction for EPB shield tunneling in sandy ground. KSCE Journal of Civil Engineering, 21(7): 2908-2918.

[12] Fang Y, Chen Z, Tao L, et al. (2019) Model tests on longitudinal surface settlement caused by shield tunnelling in sandy soil. Sustainable Cities and Society, 47: 101504.

[13] Lei M, Lin D, Huang Q, et al. (2020) Research on the construction risk control technology of shield tunnel underneath an operational railway in sand pebble formation: a case study. European journal of environmental and civil engineering, 24(10): 1558-1572.

[14] Cheng H, Chen J, Chen G. (2019) Analysis of ground surface settlement induced by a large EPB shield tunnelling: a case study in Beijing, China. Environmental Earth Sciences, 78(20).

[15] Zhang C, Han K, Zhang D. (2015) Face stability analysis of shallow circular tunnels in cohesive-frictional soils[J]. Tunnelling and Underground Space Technology, 50:345-357.

[16] Zou J, Chen G, Qian Z. (2019) Tunnel face stability in cohesion-frictional soils considering the soil arching effect by improved failure models. Computers and Geotechnics, 106: 1-17.

[17] Chen R P, Tang L J, Ling D S, et al. (2011) Face stability analysis of shallow shield tunnels in dry sandy ground using the discrete element method. Computers and Geotechnics, 38(2): 187-195.

[18] Hu X, He C, Lai X, et al. (2020) A DEM-based study of the disturbance in dry sandy ground caused by EPB shield tunneling. Tunnelling and Underground Space Technology, 101: 103410.

[19] Chambon P, Corte J. (1994) Shallow Tunnels in cohesionless soil: stability of tunnel face. Journal of geotechnical engineering, 120(7): 1148-1165.

[20] Thorpe J. (2008) Ground movement during tunnelling in sand. Queen's University (Canada).

[21] Idinger G, Aklik P, Wu W, et al. (2011) Centrifuge model test on the face stability of shallow tunnel. Acta Geotechnica, 6(2): 105-117.

[22] Lin Q, Lu D, Lei C, et al. (2021) Model test study on the stability of cobble strata during shield under-crossing. Tunnelling and Underground Space Technology, 110: 103807.

[23] Zhao L, Li D, Yang F, et al. (2019) Dimensionless parameter diagrams for the active and passive stability of a shallow 3D tunnel face. KSCE Journal of Civil Engineering, 23(2): 866-878.

[24] Zhang J, Wang W, Zhang D, et al. (2018) Safe range of retaining pressure for three-dimensional face of pressurized tunnels based on limit analysis and reliability method. KSCE Journal of Civil Engineering, 22(11): 4645-4656.