Model experiment study on the stability mechanisms of box culvert excavation faces under the effect of pipe roof in a shallow bury

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Abstract: The pipe roof box culvert construction method is widely used in short-distance crossing projects. The shallow buried tunnel can reduce the wiring length, thus saving on the project’s construction costs. However, if not handled properly, roof collapse may occur in the tunnel. In this study, we created a model experiment design based on the Tianlin Road pipe roof box culvert project and conducted an experiment involving a pipe roof box culvert excavation surface stability model under different bury depths and pipe roof stiffness levels as well as a support plate moving forward or backward. This was done to explore the process of the excavation face instability and the development mechanism of ground deformation. The excavation face support plate was moved during the experiment to simulate the failure process of the excavation face limit equilibrium state. The DIC binocular camera and the fiber Bragg grating fiber were used to monitor the surface deformation and pipe roof deformation, respectively. The experiment results reveal the environmental influence law of the supper shallow buried pipe roof box culvert construction method and the failure shape of the excavation surface. The results further indicate that the development of the surface deformation of the under-excavation gradually changes from “straight” to “parabolic” with the change of the stiffness of the pipe roof. Furthermore, without the pipe roof, both the deformation value and the ground deformation under the over-excavation do not exceed 63.4\% and 20.6\%, respectively. The maximum vertical deformation of the over-excavation pipe roof is located at about 1 H of the excavation surface, and the maximum deformation of the under-excavation occurs at a distance near 2 H. The results of the model experiment can provide guidance in the application of the pipe roof box culvert construction method under supper shallow buried conditions.
1. Introduction

With the continuous development of cities, the demand for lower traffic lanes has gradually increased. The pipe roof box culvert construction method, which can be used to better control the environmental impact during the construction process, has many advantages in crossing the project at a short distance of about 100 meters. However, if the tunnel is buried deeper, the length of the tunnel connection will be longer, and the construction site will become larger. This would lead to a sudden increase in project construction costs, which in turn, limits the further development of the pipe roof box culvert construction method. Therefore, in solving the problem of constructing a city's underpass, exploring the stability of the pipe roof box culvert construction method in the shallow buried excavation surface is of great significance, along with the broadening of the scope of application of such a construction method.

At present, the model experiment research on the stability of the tunnel excavation surface under the action of no-pipe roof has been thoroughly conducted. Li et al.\(^\text{[1]}\) proposed a physical model experiment for the dynamic excavation of a slurry balance shield. Then, they studied the mechanism of the balance of the excavation surface of the slurry balance shield and the distribution law of the settlement when the shield is moving forward. Zhu et al.\(^\text{[2]}\) carried out a physical model experiment study on pressure balance of shield construction based on the Shanghai Metro M8 line tunnel. Kirsch\(^\text{[3]}\) studied the instability mode of the excavation face characterized by dense and loose sand by conducting a series of physical model experiments. They found that loose sand showed a chimney-shaped failure, whereas the dense sand failure area did not reach the surface under the same excavation surface displacement. Such differences can be attributed to the variations in the density of sand. Liu et al.\(^\text{[4]}\) conducted a 1 g large-scale model experiment to study the stability of the excavation surface of the shallow-buried shield tunnel in dry sand, and monitored the surface settlement, supporting pressure, and internal movement of the soil. Using a semi-symmetric saturated conglomerate model experiment, Lv et al.\(^\text{[5]}\) explored the stability of the excavation surface, and obtained the fracture shape of the excavation surface as the support plate moved under different bury depths. Regarding the tunnel model experiment under the action of a pipe roof, Li\(^\text{[6]}\) explored the mechanical mechanism of the steel pipe roof by designing a model experiment with a similarity ratio of 1:25 based on the Beihong Road Tunnel Project of the Shanghai Central Ring Line. Meanwhile, Xie et al.\(^\text{[7]}\) explored the mechanism of the stability and environmental impact of the rectangular excavation surface under the action of the pipe roof by carrying out a model experiment on the pipe roof box culvert engineering based on Tianlin Road project in Shanghai. At present, most of the tunneling model experiment research have mainly concentrated on circular tunnels. Even though the research methods and conclusions have important reference and guiding significance, thus far, only a few studies have analyzed the stability of the excavation surface of the rectangular section under the action of the pipe roof.

The construction method of the pipe roof box culvert was first utilized in Japan in the 1970s. Since then, it has been rapidly developed and applied worldwide. Tan and Ranjith\(^\text{[8]}\) used FLAC to study the influence of the shape and diameter of the pipe roof on the surface settlement. They found that the pipe roof structure reduced the surface settlement by 40%–50%, thus indicating that the pipe roof structure can significantly inhibit the environment well as the tunnel deformation. Many scholars have conducted a great deal of numerical analyses, theoretical derivations, and indoor experiments based on the Shanghai Beihong tunnel project\(^\text{[6,9-11]}\). Ji et al.\(^\text{[12]}\) analyzed the ground subsidence caused by the adjacent porous jacking and took the Gongbei Tunnel as an example to conduct a three-dimensional (3D) numerical simulation of the ground subsidence caused by the jacking of three pipelines in the pipe roof. In 2019, Pan\(^\text{[13]}\) analyzed the impact of the pipe roof jacking sequence on the ground settlement based on the pipe roof project of the Guiqiao Road Station of Shanghai Line 14, and found that the water and soil cost-effectiveness greatly satisfied the actual frontal earth pressure. Xie et al.\(^\text{[14]}\) theoretically deduced the supporting pressure under the action of the pipe roof and proposed a four-
parameter calculation formula. At present, a few related projects in China are being completed. Current research on the pipe roof box culvert construction method mainly focus on the effect of the pipe roof. Only a few studies have conducted indoor model experiments on the pipe roof box culvert, and these have concentrated on the shallow bury condition. The article is based on the Shanghai Tianlin Road pipe roof box culvert underpass project. It aims to expand the traditional pipe roof box culvert construction method as well as design and carry out indoor model experiments under different bury depths and pipe roof stiffness and over-under digging conditions. This study's main objective is to explore the stability of the excavation surface of the pipe roof box culvert in shallow bury, which is of great significance in expanding the engineering application of the pipe roof box culvert construction method in future projects.

2. Model experiment design
In this work, we plan to explore the environmental impact of excavation under the action of shallow bury pipe roof through indoor model experiments. In the experiments, we controlled the displacement of the support plate in order to form the over/under excavation under the limit state. Then, the bury depth and the rigidity of the pipe roof were continuously changed to explore the influence of the bury depth and the rigidity of the pipe roof box culvert on the surrounding environment. The deformation of the surface and of the pipe roof were monitored during the experiments, along with the shape of the failure in front of the excavation surface.

2.1. Design of experiment similarity ratio and material
This experiment was based on the crossing pipe roof box culvert project under Tianlin Road in Shanghai. The cross-sectional dimensions of the box culvert are 19800×6400 mm, and the diameter of the outer pipe roof is 800 mm. The semi-symmetrical structure was selected for the model experiment under 1 g. The corresponding π matrix according to the system parameters is listed in Table 2. The similarity constant of the model experiment was derived according to Buckingham’s theorem. According to Table 2, the nine π parameters are expressed as

\[ \pi_1 = \frac{EH^2}{N}, \pi_2 = \frac{cH^2}{N}, \pi_3 = \mu, \pi_4 = \phi, \pi_5 = \frac{d}{H}, \pi_6 = \frac{D}{H}, \pi_7 = \frac{\sigma H^2}{N}, \]

\[ \pi_8 = \frac{\delta}{H}, \text{and } \pi_9 = \frac{PH^2}{N}, \]

respectively. The resemblance constants can be inferred as follows:

\[ C_e = C_c = C_p = C_\sigma, \quad (1) \]
\[ C_H = C_d = C_\phi = C_\delta, \quad (2) \]
\[ C_\mu = C_\phi = 1, \quad (3) \]
\[ C_N = C_e C_H^2. \quad (4) \]

Considering the size of the model box and the related experimental materials, the geometric similarity \( C_D \) was 50, and the elastic modulus similarity constant \( C_e \) was also 50. After performing the similarity ratio derivation, other similar relationships in the model experiment could be determined.

\[ C_p = C_p' = 50^3 \quad (5) \]
\[ C_\sigma = C_e = C_\phi = 50 \quad (6) \]
\[ C_\delta = C_\phi = 50 \quad (7) \]
\[ C_H = C_d = C_\gamma = 50 \quad (8) \]
\[ C_c = C_e = 50 \quad (9) \]
\[ C_\mu = C_\phi = 50 \quad (10) \]
The strength of the model stratum was determined according to the derivation of similarity ratios. This experiment was conducted on dry sand strata. The standard sand medium with uniform gradation was purchased on the market, and the model experiment sand was obtained by the screening method. In order to reflect the shape of the damaged soil layer, a thin layer of white sand was sprinkled on the surface of the yellow sand every 1.5 cm during the preparation of the artificial soil layer. The similarity criterion of the pipe roof was determined according to the similarity of stiffness. Finally, the acrylic round tube was used to simulate the pipe roof, and the change of the stiffness was achieved by changing its thickness and diameter.

### Table 1. The system dimension matrix

| $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $a_6$ | $a_7$ | $a_8$ | $a_9$ | $a_{10}$ | $a_{11}$ | $a_{12}$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------|----------|----------|
| $N$   | $H$   | $E$   | $C$   | $\rho$| $\mu$ | $\phi$| $d$   | $D$   | $\sigma$ | $\delta$ | $P$      |
| $F$   | 1     | 0     | 1     | 1     | 0     | 0     | 0     | 0     | 1        | 0        | 0        |
| $L$   | 0     | 1     | -2    | -2    | -4    | 0     | 0     | 1     | 1        | -2       | 1        |
| $t$   | 0     | 0     | 0     | 0     | 2     | 0     | 0     | 0     | 0        | 0        | 0        |

### Table 2. The $\pi$ matrix

| $a_3$ | $a_4$ | $a_5$ | $a_6$ | $a_7$ | $a_8$ | $a_9$ | $a_{10}$ | $a_{11}$ | $a_{12}$ | $a_1$ | $a_2$ |
|-------|-------|-------|-------|-------|-------|-------|----------|----------|----------|-------|-------|
| $E$   | $C$   | $\mu$ | $\phi$| $d$   | $D$   | $\sigma$| $\delta$| $P$      | $N$   | $H$   |
| $\pi_1$ | 1     |       |       |       |       |       |          |          |          | -1    | 2     |
| $\pi_2$ | 1     |       |       |       |       |       |          |          |          | -1    | 2     |
| $\pi_3$ | 1     |       |       |       |       |       |          |          |          | -1    | 4     |
| $\pi_4$ | 1     |       |       |       |       |       |          |          |          |       |       |
| $\pi_5$ | 1     |       |       |       |       |       |          |          |          | -1    |       |
| $\pi_6$ | 1     |       |       |       |       |       |          |          |          |       | -1    |
| $\pi_7$ | 1     |       |       |       |       |       |          |          |          | -1    | 2     |
| $\pi_8$ | 1     |       |       |       |       |       |          |          |          |       | -1    |
| $\pi_9$ | 1     |       |       |       |       |       |          |          |          | -1    | 2     |
2.2. Experiment device
The principal figure is shown in Figure 2, and the model box is shown in Figure 3.

![Figure 2. The principal figure](image)
![Figure 3. Model box](image)

For the convenience of creating the model box, the model box culvert had a cross-sectional size of 200×130 mm, the experimental box size was 1100 (along the length of the pipe roof)×1000×750 mm, and the transparent plexiglass plate was used on the symmetry plane. As it would be more convenient to observe the development process of soil damage in front of the excavation surface, the model box was provided with a rigid steel plate with four times the width, which was placed away from the excavation surface. In the experiment, the support plate was controlled using a servo motor to move forward or backward along the direction of the pipe roof. This simulated the under-excavation or over-excavation conditions of the limit equilibrium state.

2.3. Model experiment plan
In the experiment, we changed the bury depths by continuously adjusting C/H (where C is the overlying soil depth, and H is the height of the model box culvert). The limit equilibrium was formed by the forward and backward movements of the support plate. In order to explore the importance of the pipe roof stiffness, different pipe roof specifications (EI = 0.5, 0.4, 0.3, and 0) were used in the experiment. The goal was to explore the influence on the environment of the pipe roof box culvert construction method in shallow bury conditions.

2.4. The main model experiment monitoring program
The content and method of monitoring in this experiment are described as follows.

1) Monitoring ground deformation
During the experiment, a 3D DIC camera was used to monitor the model surface deformation. Before the experiment, a layer of white sand was evenly spread on top of the model stratum with the sand rain method, after which black pebbles were evenly spread on the surface of the white sand to ensure that the black-to-white ratio in the photo field of view was close to 1:1. In order to meet the accuracy requirements of this experiment, the real-time DIC acquisition frequency and the DIC camera monitoring displacement accuracy were set to 0.2 Hz and 0.00001 mm, respectively.

![Figure 4. 3D DIC measurement system of ground deformation](image)
(2) Monitoring the pipe roof deformation
To monitor the strain value of the pipe roof structure at any position in the over-under-excavation state of the excavation face, a fiber Bragg grating (FBG) sensor was arranged on the outside of the pipe roof. To monitor its strain, a set of optical fibers was arranged on the inner wall of the monitored pipe roof according to the resolution of the FBG optical fiber acquisition instrument. Each group consists of two FBG optical fibers, which were respectively glued to the top and bottom of the outer wall of the model pipe roof. A picture of the fiber layout is shown in Figure 5.

![Fiber layout](image1)

Figure 5. Fiber layout

In order to avoid the influence of the plexiglass plate and the vertical row of pipe roofs, the second, sixth, and tenth pipe roofs were selected, as shown in Figure 6. Then, the optical fibers were arranged above and below them. A total of 10 measuring points were arranged for each fiber, and the measuring points were encrypted near the excavation surface, in order to better monitor the deformation of the unloading section of the model pipe roof. The actual objects related to the fiber measurement in the experiment are shown below.

![FBG fiber measurement](image2)

Figure 6. FBG fiber measurement

3. Analysis of the model experiment results
3.1. Ground subsidence development law
The surface settlement curves of the shallow bury (C/H = 1:0.5, C/H = 1:0.3) and the different relative pipe roof stiffness (EI) values were explored in the experiments through the movements of the support plate. The results are shown below.
The development trends of surface deformation at different bury depths are similar when the support plate moves forward. When the pipe roof has a high stiffness, the ground settlement increases linearly and slowly with the support plate movement, whereas the surface subsidence increases in a “parabolic” pattern with the support plate movement when the pipe roof has a small stiffness (EI = 0.3), thus indicating that the development of surface subsidence cannot be effectively controlled when EI is 0.3. When the support plate moves backward, a clear difference in the development trend of the ground subsidence can be observed at different depths. When EI values are 1, 0.5, and 0.4, the surface settlement slowly decreases and eventually stabilizes with the support plate movement. When C/H is 1:0.5 and EI is 0.3, the surface settlement increases rapidly at first with the support plate movement; then, it is gradually reduced although it cannot be fully stabilized. Finally, when C/H is 1:0.3 and EI is 0.3, the rate of change of surface subsidence gradually decreases at first, after which it shows the characteristics of accelerated destruction.

In summary, in shallow bury, the effects of surface settlement control with different pipe roof stiffness levels are obviously different. The specific conclusions are as follows:

1) By adjusting the stiffness of the pipe roof, the pipe roof box culvert construction method can also control the surface deformation well in a shallow bury condition. The pipe roof can better control the surface deformation when the stiffness of the pipe roof is higher. The results obtained by calculating the surface deformation value under the presence or absence of the pipe roof revealed that the surface settlement value under the action of the pipe roof does not exceed 20.6% under the action of the pipe roof under over-excavation; it exceeds that without the pipe roof by 63.4%. Furthermore,
the ground deformation is significantly reduced with the increase of the moving distance of the support plate and the stiffness of the pipe roof.

(2) The value of the surface uplift caused by under-excavation in a shallow bury condition is greater than the value of surface subsidence caused by over-excavation. At the same time, the more shallow the bury depth is, the greater the value of the surface uplift due to under-excavation. The change in surface settlement caused by over-excavation at different depths is less obvious. Therefore, the under-excavation conditions during construction should be controlled.

(3) In a shallow bury condition, we can choose a relatively small stiffness of pipe roof to control the deformation of the ground. Doing so can help save on project costs. When the support plate moves forward and the stiffness of the pipe roof gradually decreases, the increase rate of the surface bulge gradually accelerates. The trend gradually changes from “straight” to “parabolic” in this case. When the support board moves backward and the stiffness of the pipe roof is sufficient, the stability of the surface settlement can be maintained even with the movements of the support plate. When the stiffness is insufficient, the surface deformation will eventually show an accelerated failure trend.

3.2. **Pipe roof deformation distribution law**

When the moving distance of the support plate is 20 mm, the deformation value of each point of the pipe roof, which is measured by the optical fiber in the experiment, can be fitted in the final pipe roof deformation diagram shown in Figure 9 and Figure 10. On the one hand, when the support plate moves backward, ground deformation can be divided into four sections: (1) warped section: at this time the deformation of the pipe roof increases rapidly and reaches the positive maximum value; (2) acceleration descent section: it rapidly decreases from the positive maximum value to less than 0; (3) settlement section: at this time, the deformation of the pipe roof is large, and this section is also an important concentration place of surface settlement; and (4) the micro settlement section: this is marked by the small deformation of the pipe roof along its length. On the other hand, when the support plate moves forward, the deformation of the pipe roof can be divided into four sections (1) micro-uplift section: the pipe roof slightly deforms upwards at this time; (2) acceleration ascent section: the pipe roof's upward deformation rapidly increases; (3) uplift section: at this time, the upward deformation of the pipe roof reaches the maximum, corresponding to the main concentrated section of the surface uplift; and (4) slow decline section: at this time, the deformation of the pipe roof decreases slowly.

![Figure 9. Deformation diagram of pipe roof with different stiffness levels, C/H = 1:0.5](image-url)
The deformation value of the pipe roof varies under different bury depths, but the overall trend is similar. The deformation value of the pipe roof is greater when the moving distance of the supporting plate is the same, the bury depth ratio is the same as the C/H, and when the stiffness of the pipe roof is smaller. The deformation value of the middle pipe roof is higher than the deformation values of both sides in the direction of the excavation surface; moreover, the deformation value of the pipe roof near the glass plate is higher than the deformation value of the side near the vertical pipe roof, which is consistent with the distribution range of the surface deformation.

On the one hand, when the support plate moves backward, the bury depth ratio is greater, and the deformation value of the pipe roof is greater. On the other hand, when the support plate moves forward, the bury depth is smaller, the weight of the soil above the pipe roof is smaller, and the deformation of the pipe roof uplift is stronger. Furthermore, the deformation of the pipe roof when the support plate is advancing is greater than the settlement deformation of the pipe roof when the support plate is moving backward. Therefore, for the deformation of the pipe roof, the under-exavation condition should be controlled in the shallow bury. The maximum vertical deformation of the over-exavation pipe roof is located near 1 H from the excavation surface, and the maximum under-exavation occurs near 2 H from the excavation surface.

3.3. Shape of the excavation surface damage

By taking pictures of the destruction shapes in front of the excavation surface, the failure shapes of the excavation surfaces were analyzed under different pipe roof stiffness levels and bury depths.

(1) Comparison of the failure shapes of the excavation surfaces as the supporting plate moves forward and backward

As shown in Figure 11(a), when the support plate moves forward, the soil in front of the excavation surface moves obliquely in a “wedge-shaped” manner in front of the excavation surface, resulting in a large surface uplift in front of the excavation surface. The soil above the pipe roof is severely disturbed due to the deformation of the pipe roof, as shown by the white sand line in Figure 11(b). When the supporting plate moves backward, the soil in front of the excavation surface and below the pipe roof has the shape of a “chimney,” which is similar to the destruction shape under the pipe roof. Above the pipe roof, a settlement groove is formed on the surface, and the pipe roof blocks the “chimney” development of the shape of the surface damage. Thus, the range of influence on the surface in front of the excavation surface is limited.
(2) Comparison of the failure shapes of the excavation surfaces under different bury depths
When the support moves backward, the soil under the pipe roof is “wedge-shaped” in a shallow depth. After passing through the pipe roof, the deformation of the soil layer above the pipe roof is gradually weakened to the surface due to the blocking effect of the pipe roof, and the whole shape becomes that of a “chimney.” The soil layers under and above the pipe roof interact with each other, with the soil under the pipe roof providing support. The soil under the pipe roof and that above it move more than the soil on top of the pipe roof; thus, they may form a separate “wedge-shaped” failure surface until the soil layers above and below the tube roof have little mutual influence, and the pipe roof basically bears the deformation of the overlying soil in the “vacant area.” As shown in Figure 13, when the support plate moves forward, the more shallow the bury depth is, the more obvious the soil layer displacement in front of the excavation surface and the greater the disturbance of the pipe roof deformation on the soil above it.

Figure 12. Failure shapes of the excavation surfaces of the support plate moving backward under different bury depths, EI = 1 L = 20 mm

Figure 13. Failure shapes of the excavation surfaces of the support plates moving forward under different bury depths, EI = 1 L = 20 mm

(3) Comparison of the failure shapes of excavation surfaces under different pipe roof stiffness levels
The different failure shapes of the excavation surfaces under different pipe roof stiffness are shown in Figure 14. When the stiffness of the pipe roof is sufficient, the soil below the pipe roof forms an “empty area.” When the stiffness of the pipe roof is insufficient, the soil in front of the excavation surface develops to the surface in the shape of a “chimney.”
4. Conclusion

By conducting an indoor physical model experiment, this paper explores the excavation surface stability of the pipe roof box culvert and obtains the surface deformation development law, the pipe roof deformation law, and the failure shapes of the excavation surfaces. The specific conclusions are as follows:

(1) The stiffness of the pipe roof has a significant impact on the surface deformation. With the improvement of pipe roof stiffness, the effect increases at first but becomes less obvious as the stiffness improves. When the support plate moves backward, the surface settlement value under the action of the pipe roof does not exceed 20.6% than that without the action of the pipe roof. When the support plate advances, the surface uplift value under the action of the pipe roof does not exceed 63.4% than that without the pipe roof; this value decreases significantly as the support plate moves and the stiffness of the tube roof increases.

(2) The surface uplift is caused by the support plate advancing more severely than the surface settlement caused by the support plate backward in shallow bury depths.

(3) The change of the pipe roof stiffness has a significant effect on the surface deformation. When the supporting plate advances and the pipe roof stiffness gradually decreases, the surface uplift increases gradually. The trend gradually changes from “linear” to “parabolic” when the supporting plate moves backward. When the stiffness of the roof is sufficient, the ground settlement with the movement of the support plate can eventually remain stable. However, when the stiffness is insufficient, the surface deformation eventually shows an accelerated failure trend.

(4) The overall trends of pipe roof deformation are similar. When the bury depth ratios are the same, the greater the pipe roof stiffness, the smaller the deformation would be. The horizontal distribution of the pipe roof is large in the middle and small on both sides. The deformation value of the horizontal pipe roof near the vertical pipe roof is significantly reduced. At the same time, the deformation of the under-excavated pipe roof is obviously greater than that of the over-excavation condition. The maximum vertical deformation of the over-excavation pipe roof is located near 1 H from the excavation surface, whereas the maximum under-excavation occurs near 2 H from the excavation surface.

(5) The failure shape of the excavation surface is related to the bury depth and the stiffness of the pipe roof. When the support plate moves backward, the “void area” is formed in front of the excavation surface, and the destruction shape takes the form of a “wedge” if the stiffness of the pipe roof is sufficient. The pipe roof bears most of the deformation of the upper soil body. The failure shape of the excavation surface has the form of a “chimney” if the rigidity of the pipe roof is insufficient, and the soil body below the pipe roof has an effect on the soil above with the pipe roof. The deformation of the pipe roof causes severe disturbance to the soil above it under three conditions: when the supporting plate moves forward, when the stiffness of the pipe roof is low, and when the soil...
in front of the excavation surface is displaced diagonally upwards. In such a case, the smaller the bury depth is, the more significant the disturbance generated.

Acknowledgments
This research was funded by the National Key R&D Program of China (Grant Nos. 2018YFC0809601 and 2018YFC0808702) and by the Shanghai Science and Technology Development Funds (Grant Nos. 18DZ1205200 and 17DZ1204101).

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