Finite Element Analysis of Pipe Shed Pre-Supporting Reinforcement Effect on A Shallow-Buried Tunnel

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Abstract. Under the engineering background of crushed zone at the entrance section of a shallow-buried soft rock tunnel, the 3D finite element simulation of pipe shed pre-reinforcement measures was implemented under different diameters, lengths, and spacing via Midas Civil software after the excavation of tunnel portal, in an effort to analyze the reinforcement principle of pipe shed grouting reinforcement method during the tunnel excavation process. The stress-induced deformation laws of the support system were summarized, and the reinforcement effect of pipe shed grouting method was analyzed. The results show that with the increase in diameter of pipe shed, the maximum deformation of pipe shed is obviously reduced, and the favorable effect is reached when the diameter of pipe shed is within 300-600 mm. As the pipe shed extends to the undisturbed zone of soil mass, the change in length has a very minor effect on the deformation of pipe shed, while the deformation is greatly impacted by the excavation footage, and the deformation becomes the most significant after the excavation footage becomes greater than 1.5 m.

1. Project overview
Extending from the northwest to the southeast direction, a tunnel is a separating-type two-way four-lane tunnel parallelly arranged along the left and right lines, where the maximum burial depth is 140 m, the minimum burial depth is only 11 m (in the crushed zone of the entrance section), and the full length is 1,353 m. The excavation length and height of the tunnel are 10.796 m and 8.6 m, respectively. The excavation is implemented through the three-bench tunneling method[1]. The digging length of upper bench is 0.6 m, and core soil is reserved with length kept within 5-6 m. The digging length of middle bench is 1.5 m and that of lower bench is 2 m, and supporting measures are timely taken after the excavation of each bench. Composite linings are used for initial supporting of the upper soft rock zone, along with reinforced support using double-layer section steel frames, and the tunnel dimensions[2] are shown in Figure 1.
2. Difficulty analysis of the Project

The steel arch supports are connected to the initial supports to form a whole. The connection between initial supports at the portal section is reinforced, and finally a support system combining arch supports with initial supports and combining initial supports is formed. This combined system[3] is mainly composed of two parts, namely, connection between steel arch supports and initial supports, and that between initial supports, and the cross section of the pipe shed is displayed in Figure 2.

![Figure 2 Cross-Sectional View of Pipe Shed](image)

The diameter of pipe shed used is 108 mm, the length of each section is 3 m, and the total length is 40 m. The pipe shed is arranged circumferentially along the tunnel vault at spacing of 50 cm, and the overlap distance of the pipe joints is not less than 2 m as shown in Figure 3. The cement paste-water glass mixture is grouted into the steel pipes to ensure the integrality of leading pipe shed, and the pipes are then compactly filled with M30 cement mortar to enhance the stiffness and strength of pipe shed.

![Figure 3. Site Picture of Pipe Shed](image)
3. Reinforcement mechanism analysis

The pipe shed pre-grouting reinforcement can realize the following effects: (1) Beam effect. The front end of leading pipe shed is driven into the intact rock mass around the tunnel to generate an anchoring effect, and it is combined with the initial supports arranged along the excavation direction to jointly bear the stress brought by slip cracking in the crushed zone of tunnel surrounding rocks, thus exerting the pre-reinforcement effect of supports. (2) A reinforcing ring is formed. As shown in Figure 4, a leading pipe shed is arranged along the tunnel excavation direction, and thus a relatively stable rock mass is formed to reinforce the arch foot and support the tunnel arch ring, so as to reach a balanced state. The surrounding rocks are reinforced and compacted by injecting grout in the hole reserved at the front end of the pipe shed, so the overall stability of the tunnel is enhanced considerably, and the construction safety is guaranteed.

![Figure 4. Pipe Shed Reinforcement Mechanism: Formation of Reinforcing Ring](image)

3.1 3D Numerical Analysis

The dimensions of the calculation model are 180m*140m*50m (length*width*height). Fixed boundary conditions[4] are adopted, where fixed constraints are used at the bottom, equivalent load is applied 19 m above the tunnel vault, and fixed constraints are applied at the boundary of two ends along the horizontal direction. The change in stress and displacement is small at a place distant from the excavation part, the change rate of stress at 3/1 span is generally below 5%, so the model breadth satisfies the accuracy requirement. The hexahedral elements are used for the stratum and shell elements for the tunnel lining. There are totally 64,200 hexahedral elements and 3,160 shell units. The overall model of this tunnel is presented in Figure 5.

![Figure 5. Overall Model of Tunnel](image)

In consideration of the support delay effect caused by the early strength of shotcrete, namely, the strength will reach a stable value only after the supporting measure is taken for six cycles, and the supporting intensity during this period is assumed to present spatial linear growth. In the supporting of the previous bench, the excavation area of each bench and excavation sequence were simulated according to the actual construction, and the cyclic excavation simulation was carried out through the build-in function of the 3D simulation software[5-6].
3.2 Numerical Simulation Results

3.2.1 Pre-reinforcement analysis of pipe shed under different diameters

The deformation trends of pipe shed under different diameters and the relationship between the deformation of support system and diameter of pipe shed obtained through the 3D numerical simulation are shown in Figure 6.

![Deformation trend chart of pipe shed under different diameters](image1)
![Relationship between deformation of support system and diameter of pipe shed](image2)

Figure 6. Deformations of Tunnel Support System under Different Diameters of Pipe Shed

The deformation curve distribution patterns of pipe shed under different diameters were similar, and the maximum deformation took place in the plastic disturbance zone in front of the tunnel face. It could be further observed from Figure 6 that with the increase in diameter of pipe shed, its deformation showed a declining trend but not linear decrease. When the diameter of pipe shed ranged from 79 to 300 mm, the maximum deformation was reduced from 35 mm to 23 mm. As the diameter was elevated from 300 mm to 600 mm, the deformation was reduced from 23 mm to 16 mm. $\xi=0.054$ within diameter of 79-300 mm, and $\xi=0.023$ within 300-600 mm, so the former was about twice of the latter.

3.2.2 Pre-reinforcement analysis under different lengths of pipe shed

![Deformation trend chart of pipe shed under different lengths](image3)
![Relationship between deformation of support system and length of pipe shed](image4)

Figure 7. Deformations of Tunnel Support System under Different Lengths of Pipe Shed

As shown in Figure 7, for the pipe shed with diameter of 108 mm, its deformation curves were nearly overlapped with the increase in length, indicating that only if the pipe shed extends into the undisturbed zone, the change in length will almost have no influence on the deformation of pipe shed. During the practical construction, the pipe shed can be driven segment by segment, and attention should be paid to the overlap between the segments. Moreover, the pipe shed should be over the tunnel face for a certain
distance, namely, the pipe shed is stretched to the front of elastic-plastic disturbed zone of the tunnel face.

3.2.3 Pre-reinforcement analysis of pipe shed under different spacing

![Deformation trend chart of pipe shed under different spacings](image1)
![Relationship between deformation of support system and pipe shed spacing](image2)

Figure 8. Deformations of Tunnel Support System under Different Pipe Shed Spacings

As shown in Figure 8, the change in excavation footage of pipe shed had no influence on the overall deformation distribution of pipe shed, but the maximum deformation was significantly influenced by the excavation footage. The maximum deformation under $s=2$ m was 2.7 times of that under $s=0.6$ M, and that under $s=3$ m was 5.7 times of that under $s=0.6$ m, more clearly indicating the relationship between excavation footage and growth rate of pipe shed deformation. Furthermore, the trend line I was much more even than trend line II, manifesting that the deformation of pipe shed was remarkably enlarged after the excavation footage was greater than 1.5 m. As supporting measure was not taken, the pipe shed was not supported underneath, the overlying load was fully borne by the pipe shed, which was equivalent to the fixed-end beam body embedded at two ends, and its deformation (deflection) would be certainly enlarged with the increase in the beam span. Therefore, the excavation footage should be strictly controlled when the three-bench method is used in the practical hole excavation process, in order to avoid the collapse triggered by the excessive deformation of tunnel vault.

4. Conclusions.

Based on a summary of studies carried out by many domestic (Chinese) and foreign scholars, two core effects of pipe shed pre-reinforcement were analyzed: 1) The beam constraint effect is formed, namely, the front end of the leading pipe shed is driven onto the intact rock mass around the tunnel to form the anchoring effect and jointly undertake the stress brought by the slip cracking in the crushed zone of tunnel surrounding rocks, thus exerting the supporting-based pre-reinforcement effect. 2) A reinforcing ring is formed, a leading pipe shed is arranged along the tunnel excavation direction, and a relatively stable rock mass is generated to reinforce the arch foot and support the tunnel arch ring, which will contribute to the balanced state. The main conclusions are drawn as follows:

1) When the diameter of pipe shed changes within 79-300 mm, the maximum deformation of pipe shed is reduced from 35 mm to 23 mm. The deformation will be decreased from 23 mm to 16 mm as the diameter of pipe shed is enlarged from 300 mm to 600 mm.

2) When the pipe shed is stretched into the undisturbed zone, the change in length will almost have no influence on the deformation of pipe shed.

3) As for the relationship between the excavation footage and growth rate of pipe shed deformation, the trend line I is much more even than trend line II, indicating that the deformation of pipe shed is significantly enlarged after the excavation footage is larger than 1.5 m.
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