Force and deformation mechanism of great pipe shed advanced support in subway tunnel

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Abstract. Taking the construction of a certain section of Guiyang rail transit as an example, the theoretical analysis of the stress conditions and constraints of the pipe shed during tunnel excavation is carried out for the support parameters of the large pipe shed. By analyzing the force of the micro-segment of the pipe shed, bringing the Bernoulli-Euler beam theory formula into the equilibrium equation of the micro-segment, the governing differential equations of the pipe shed at the vault and the non-arch is obtained. Two types of pipe sheds are designed, and the numerical simulation of the tunnel with two structural forms of tunnel with advanced support of large pipe shed is carried out by using MIDAS/GTS NX finite element software, and the displacement and stress of the pipe shed are obtained and the theoretical verification is carried out. By comparing the displacement and vertical stress of the large tubular awning in plan 1 and plan 2, it is concluded that plan 2 is more reasonable and has better bearing capacity.

1. Research Background

The tunnel is often supported by the pipe shed method for the weak and easy collapsed surrounding rock and the strict requirements for settlement in tunnel construction. Belgium first used the technology in the construction of the Antwerp metro station in the 1970s[1], and the technology was rapidly developed [2-3]. Using the pipe shed to pre-treat the surrounding rock can improve the integrity and stability of surrounding rock, and its deformation can be inhibited. Its function is reflected in many engineering examples: the fault-breaking zone of the Slope Tunnel of the Yuzitang Hydropower Project[4] is treated by the pipe shed method to ensure the safe construction. Harbin Rail Transit Line 1 Education Square Station No.1 and No.2 air duct[5] adopts a large pipe shed for advanced support, and its settlement value is within the predetermined settlement range. The tunnel entrance of Houshanwu Tunnel in the reconstruction project of Linpu section from Hangzhou to Xiaoshan Ring Expressway[6] is used for pipe shed construction to achieve safe entry into the hole.

Many research results has been achieved on the design, construction technology and application effect of the pipe shed. These results can be summarized into four aspects: analytical solution, numerical simulation, model test and field test. In terms of analytical research, Wu Jianwei [7] comprehensively and dynamically analyzes the stress process of each section of the pipe shed during the excavation process according to the initial parameter solution of the classic Winkler model, and proposes the calculation equation of the whole section of the pipe shed during the excavation process;
Jia Jinqing [8] Based on the Pasternak elastic foundation beam theory, the deflection equation and internal force calculation formula of the pipe shed are derived, and the solution method is proposed. Mo Linhui[9] from the perspective of structural mechanics, the mechanical model of action of the tunnel support pipe shed is established by the theory of elastic foundation beam. In terms of numerical research, Guo Yanjing [10] used the one-time application of the 126m advanced large pipe shed of Huangzhuang Station of Beijing Metro Line 10 as the research background. Based on the analysis of the effect and mechanism of the pipe shed, the existing pipe was compared on the advantages and disadvantages of the shed calculation model. Li Chao[11] studied and analyzed the mechanism of pre-reinforcement of shallow-buried tunnel excavation pipe shed and advanced small pipe shed grouting. Xu Delong[12] took the geological conditions of the water-rich sand layer in the excavation tunnel of Hexi Station-Hedong Station Section of Civil Engineering No. 10 of Qingdao Metro Phase I (Line 3) as an example, using MIDAS/GTS finite element software to simulate and analyse the displacement of surrounding rock during and without grouting Field situation. Taking a deep tunnel landslide as an example, Han Jizhen[13] simulated the deformation of surrounding rock during pre-reinforcement with and without pipe shed by MIDAS/GTS NX. In addition, a series of research results have been obtained in model tests and field tests[14-16].

In the numerical simulation of tunnels with advanced support for pipe sheds, many scholars[17-18] usually equate the reinforcement effect of the pipe shed to surrounding rock as an annular reinforcement zone, but failed in getting force deformation information. In order to study the mechanism of stress deformation of pipe shed, this paper firstly analyses the deformation mechanism of pipe shed by theory, and then considering the problem of pipe shed support of constructs the tunnel of Guiyang Rail Transit Line 1 station to Shachong Road Station (hereinafter referred to as fire-sand tunnel), considering the role of grouting reinforcement zone + pipe shed, the problems of pipe shed deformation, stress change law and pipe shed structure change on tunnel surrounding rock deformation are studied.

2. Pipe shed force deformation mechanism

Before the tunnel is excavated in the soft and easy collapse section, the pipe shed is often used to support the surrounding rock of the tunnel. When pipe shed was applied, the grouting small pipe can both strengthen the local surrounding rock and support it, the grouting small pipe is in equilibrium with the ground reaction force and the surrounding rock pressure and the constraint conditions. The surrounding rock pressure can be divided into two cases: ① The pipe shed at the tunnel vault is affected by the vertical surrounding rock pressure and the horizontally symmetric horizontal surrounding rock pressure. ② The pipe shed at the non-arched position is subjected to vertical surrounding rock pressure and asymmetrical horizontal surrounding rock pressure. The force diagram of the pipe shed is shown in Figure 1. Before the tunnel excavation, the big pipe shed is arranged in the circumferential direction of the tunnel arch to support the tunnel. The force and restraint state of the shed is shown in Figure 1(a), where the deflection of point A on the pipe shed is \( \omega_A = 0 \). When the tunnel starts from excavation to a certain distance, the influence of tunnel excavation on the pipe shed only reaches point B. The BC section of the pipe shed is not affected by tunnel excavation. At point B, the pipe shed is subject to fixed restraint deflection \( \omega_B = 0 \), at this time the force and restraint state of the pipe shed is shown in Figure 1(b-1). When the tunnel continues to be excavated, its influence on the pipe shed has reached the full length of the pipe shed. At this time, the force and restraint state of the pipe shed is shown in Figure 1 (b-2). when the tunnel is excavated to point C, the force and restraint state of the shed is shown in Figure 1 (b-3).
A micro-segment $dx$ is taken from the pipe shed, and its force is shown in Figure 2. According to the equilibrium condition of the micro-segment $\Sigma F_y = 0$ and $\Sigma M = 0$, the formula 1 and the formula 2 are respectively obtained, and the formula 2 is brought into the formula 1, then the formula 3 is obtained. Bringing the Bernoulli-Euler beam theory formula into Equation 3, the deflection differential equation 4 of the pipe shed is obtained.

\[
\frac{dQ(x)}{dx} = d\times[p(x) - q(x)] 
\]

\[
Q(x) = \frac{dM}{dx} 
\]

\[
\frac{d^2 M(x)}{dx^2} = d\times[p(x) - q(x)] 
\]

\[
EI \frac{d^4 \omega(x)}{dx^4} = d\times[q(x) - p(x)]
\]

The vertical surrounding rock pressure of pipe shed is related to the buried depth of tunnel, and using 2~2.5 times average height of the square as the boundary of the deep and shallow tunnel [19]. The calculation of the boundary depth is shown in Equation 5~6, where $H_p$ is the depth of the deep and shallow buried tunnel, $h_q$ is the average height of the square, $s$ is the surrounding rock grade of the tunnel, $\zeta$ is the width influence coefficient. When the tunnel buried depth $H < H_p$, the tunnel belong to shallow buried tunnel, the vertical surrounding rock pressure acting on the pipe shed is divided into two cases. ① When the tunnel depth $H < h_q$, the vertical surrounding rock pressure $q_1$ acting on the pipe shed is the total weight of the overlying rock, see Equation 7. ② When the tunnel burial depth $h_q < H < H_p$, $q_1$ is shown in Equation 8. When the tunnel depth $H > H_p$, it is a deep buried tunnel, and the vertical surrounding rock pressure $q_1$ acting on the pipe shed is shown in Equation 9.

\[
H_p = (2 \sim 2.5) \cdot h_q
\]

\[
h_q = 0.45 \times 2^{0.5-s} \cdot \zeta
\]

\[
q_1 = \gamma H
\]
\[ q_1 = \gamma H \left( 1 - \frac{H}{B_1 \lambda \tan \theta} \right) \]

\[ q_1 = 0.45\times 2^{x/4} \times \gamma \omega \]  

(8)  

(9)  

The ground reaction force of the pipe shed is calculated by the Pasternak model. The Pasternak model assumes that there is shearing between the spring elements in the Winkler model. The shearing action passes through a shear layer that can only produce transverse shear deformation but incompressible. The relationship between ground reaction force and displacement is shown in Equation 10.

\[ p(x) = k_0(x) - G_p \frac{d^2 \phi(x)}{dx^2} \]  

(10)  

2.1. Stress deformation mechanism of pipe shed at the top of the arch

The pipe shed at the tunnel vault is subjected to the pressure of the left and right symmetrical horizontal surrounding rock, that is, \( e_L = e_R \), the pressure of the surrounding rock on the pipe shed is equal to the vertical surrounding rock pressure, see Equation 11. Equation 10 and Equation 11 are brought into the deflection differential equation 4 of the pipe shed to obtain the governing differential equation 12 of the pipe shed at the vault. According to the difference of the buried depth of the tunnel, the different \( q_1 \) is introduced, and then the formula 12 is integrated and brought into the pipe shed boundary condition to obtain the deflection equation of the pipe shed at the vault.

\[ q(x) = q_1 \]  

(11)  

\[ EI \frac{d^4 \phi(x)}{dx^4} - \frac{d^2 \phi(x)}{dx^2} G_p d = \left[ q_1 - k_0 \phi(x) \right] d \]  

(12)  

2.2. Stress deformation mechanism of pipe shed at non-arch

The pipe shed at the non-arch of the tunnel is subjected to asymmetrical horizontal rock pressure, that is \( e_L \neq e_R \). The lateral force of the pipe shed in the upper right part of the tunnel is shown in Figure 3. Since the pipe shed is very close to the tunnel, see \( e_L = 0 \), the pressure of the surrounding rock on the pipe shed is shown in Equation 13, and Equation 10 and Equation 13 are brought into the deflection differential equation 4, A control differential equation 14 is obtained for the non-arched pipe shed. According to the difference of the buried depth of the tunnel, different \( q_1 \) is brought in, and then the deflection equation of the non-arched pipe shed is obtained by integrating the formula 14.

\[ q(x) = \sqrt{\left( q_1 \right)^2 + \left( e_{\phi} \right)^2} \]  

(13)  

\[ EI \frac{d^4 \phi(x)}{dx^4} - \frac{d^2 \phi(x)}{dx^2} G_p d = \left[ \sqrt{\left( q_1 \right)^2 + \left( e_{\phi} \right)^2} - k_0 \phi(x) \right] d \]  

(14)  

3. Numerical simulation analysis

3.1. Project overview

The fire-sand tunnel is located in Nanming District of Guiyang City. After throughing the railway station, the line passes through the train station ticket office, the private room, the passenger platform, the railway track and the expressway tunnel, finally arrives at the Shachong Road Station. The completion map data of the station building indicates that the ticketing hall and the row room are all pile foundations. In order to control the ground settlement caused by tunnel excavation, the tunnel is supported by the large pipe shed before the tunnel excavation.
3.2. Finite element model establishment and parameter selection

The span of the fire-sand tunnel passing through the station section of the railway station is 5m. The specification of the advanced support large-tube shed is a hot-rolled seamless steel tube with an outer diameter of 159mm, a wall thickness of 10mm and a circumferential tube spacing of 35cm. In order to improve the bending resistance of the pipe shed, a steel cage is added in the pipe shed and concrete is filled in it, as shown in Figure 4. In the 180° range of the arch section under the station section, the large pipe shed is used for advanced support; the full-section excavation is adopted, the excavation footage is 0.35~0.50m; the average buried depth of the tunnel is H=16m; The first branch is made of 36cm thick C30 shotcrete and the second line is made of 65cm thick C35 waterproof reinforced concrete.

![Figure 3. Transverse force diagram of pipe](image1)

![Figure 4. Great pipe shed and steel cage shed in the upper right part of the tunnel](image2)

| Table 1. Model parameters |
|---------------------------|
| category | Layer thickness (m) | Severe (KN m⁻³) | Elastic modulus (GPa) | Poisson's ratio | Cohesion (MPa) | Internal friction angle(°) |
|-----------|---------------------|-----------------|----------------------|----------------|----------------|--------------------------|
| Subgrade  | 2.0                 | 20              | 0.08                 | 0.3            | 0.028          | 25                       |
| Filling   | 1.5                 | 19.5            | 0.007                | 0.42           | 0.01           | 10                       |
| Red clay  | 5.0                 | 17.0            | 0.012                | 0.37           | 0.05           | 15.35                    |
| Mud dolomite | 43.5            | 24.2            | 14.49                | 0.22           | 3.518          | 39.10                    |
| Steel Pipe |                    |                 |                      |                |                |                          |
| Filling concrete | 23             | 29.5            | 0.2                  |                |                |                          |
| Initial branch  | 0.36          | 23.6            | 25                   | 0.21           |                |                          |
| Second lining   | 0.65           | 25              | 32                   | 0.20           |                |                          |
| Anchor         | 200               |                 | 0.25                 |                |                |                          |

In order to study the deformation and stress variation of the pipe shed, analyze the influence of the pipe shed structure on the deformation of the surrounding rock of the tunnel. The MIDAS/GTS NX numerical simulation software was used to establish a three-dimensional solid model, the parameters are shown in Table 1. The model size is length × width × height = 50m × 10m × 50m. In the pipe shed, only concrete is filled as the plan 1. On the basis of plan 1, the steel cage is added as the plan 2, the cross section is shown in Figure 5, and the parameters are shown in Table 2. The bending resistance of the pipe shed and the deformation of the tunnel surrounding rock are compared and analyzed.

| Table 2. Parameters of pipe shed |
|----------------------------------|
| Pipe shed parameters | Pipe distance (cm) | Outer diameter (mm) | Wall thickness (mm) | Steel cage (mm) | Concrete |
| plan 1                  | 350              | 159               | 10                |              | C25      |
| plan 2                  | 350              | 159               | 10                | 4*18         | C25      |
The numerical simulation makes the following assumptions:

1. All materials are continuous, uniform and isotropic;
2. Does not consider the influence of groundwater and cave;
3. Surface level and only consider the self-heavy stress field;
4. Regardless of the formation of the reinforcement zone by the grouting of the pipe shed, only the influence of the pipe shed on the tunnel excavation is considered.

In order to make the numerical simulation results more realistic, 3D solid elements are used for steel pipes, steel bars, primary support, second linings, tunnels and surrounding rock, 1D implanted truss units are used for anchors, Mohr-Coulomb strength criterion is adopted for the model. The construction step length is 0.5m, the anchor rod is arranged in a plum blossom shape, the circumferential direction*vertical direction=1.0m*0.7m, and the tunnel excavation, the initial support for the application and the second lining are separated by one construction step. The mesh of the finite element model is shown in Figure 6. The tunnel is excavated along the y-axis.

4. Pipe shed force deformation law and analysis

In the actual project, the role of numerical simulation is irreplaceable because of the inability to conduct on-site tests. The plan 1 is taken as the research object to study the displacement and stress variation of the pipe shed during the excavation of the tunnel.

4.1. Pipe shed displacement change law

In order to study the displacement variation law of the pipe shed, the displacement change data of the points at the front end, the middle and the rear end of the pipe shed (points at the tunnel axis y=0m, y=5m, y=10m) are shown in Figure 7. The displacement variation of the entire length of the pipe shed when the tunnel is excavated to the tunnel axis at y=0.5m, y=5m, and y=10m is shown in Figure 8.

In Figure 7, curve 1 indicates that with the tunnel excavation, the displacement change at the front end of pipe shed gradually becomes smaller, and the final displacement tends to a fixed value, curve 2 indicates that the displacement change in the middle of the pipe shed increases first when the tunnel excavation, the initial support for the application and the second lining are separated by one construction step. The mesh of the finite element model is shown in Figure 6. The tunnel is excavated along the y-axis.

In Figure 8, the curve A indicates that when the front end portion of the tunnel is excavated, the displacement of the pipe shed is changed only within a certain range from the front end portion of the tunnel, and it does not change substantially at a distance from the front end portion of the tunnel. Curve B shows that when excavation to the middle of the tunnel, from the front end face of the tunnel to a certain extent behind the excavation face, the rate of change of displacement of the pipe shed is very small, from a certain extent at the rear of the excavation face to the front of the excavation, the
displacement of the pipe shed occurs rapidly. The curve C indicates that the displacement rate of the pipe shed is small at the rear of the excavation face when excavating to the rear end face.

4.2. Change law of vertical stress of pipe shed

In order to study the vertical stress variation law of pipe shed, the vertical stress variation data of the tunnel excavation at the points at the front, middle and rear ends of the pipe shed (points at the tunnel axis y=0m, y=5m, y=10m) are shown in the figure 9. The variation of the full length of the pipe shed when the tunnel is excavated to the tunnel axis at y=0.5m, y=5m, and y=10m is shown in Figure 10.

In Figure 9, curve 4 indicates that the vertical stress at the front end of the pipe shed is drastically reduced when the tunnel is started to be excavated. When the tunnel is excavated to a certain distance in front of the point, the vertical stress tends to be gentle at that point. Curve 5 indicates that the vertical stress of the central part of the pipe shed does not change much when the tunnel begins to excavate. As the tunnel continues to excavate, the vertical stress at this point decreases sharply. When the tunnel is excavated to a certain distance in front of the point, the vertical stress tends to be gentle at that point, the curve 6 changes the same as curve 5.

In Figure 10, the curve D indicates that when the tunnel is started to be excavated, the vertical stress drop on the pipe shed is only a part of the pipe shed that is closer to the front end surface of the tunnel, and the vertical stress at the pipe shed far from the tunnel excavation surface is basically no change occurs. Curve E indicates that the vertical stress of the pipe shed tends to be fixed at the rear of the tunnel excavation face, and it changes sharply within a certain range in front of the excavation face. Curve F indicates that the vertical stress of the pipe shed tends to be fixed behind the excavation face.

4.3. Analysis of the law of deformation of pipe shed

The law of displacement and vertical stress of the pipe shed indicates that when the tunnel starts to excavate but is not supported, the excavation part is in a suspended state. Under the action of the surrounding rock pressure in the suspended position and its front part, the pipe shed has a downward displacement in this range. Within the range, surrounding rock generates corresponding displacement, and it generates stress release. The pressure of the surrounding rock decreases in this range. When the
pressure of the surrounding rock in this range is equal to the reaction force of the surrounding rock in
the range, the pipe shed is in equilibrium, and its stress state is shown in Figure 1 (b-1). When the
tunnel is excavated to the middle, under the pressure of the surrounding rock in the suspended area of
the pipe shed and the front and rear parts of the tunnel, the downward displacement of the pipe shed in
this range occurs, and the surrounding rock is displaced accordingly. The stress is released from the
surrounding rock, and its stress is reduced. When the surrounding rock stress in this range is equal to
the sum of the reaction force of the supporting foundation and the reaction force of the surrounding
rock foundation, the pipe shed reaches an equilibrium state, and the stress state is shown in Figure 1
(b-2). When the tunnel is excavated to the rear end, the rear end of the pipe shed is suspended. Under
the pressure of the surrounding rock within a certain range of the upper part and the rear part, the pipe
shed has a downward displacement, and the surrounding rock occurs correspondingly displacement,
the stress release, and its stress decreases. When the surrounding rock stress in this range is equal to
the reaction force of the supporting foundation, the pipe shed reaches an equilibrium state, and its
stress state is shown in Figure 1 (b-3). It should be pointed out that the p(x) in the theoretical
calculation only indicates the loose surrounding rock pressure, that is the final surrounding rock
pressure, so the displacement of the surrounding rock calculated by the theoretical formula is the final
displacement of the pipe shed.

5. Structural comparison analysis
The structure of pipe shed has a great influence on its bearing capacity, and the rationality of its
selection will directly affect the tunnel support effect. To this end, by comparing the displacement and
stress of pipe sheds of the two plans in the tunnel excavation, a more reasonable structural form is
selected.

The comparison of the displacement and vertical stress of the large pipe sheds of the two structural
forms is shown in Figure 11 and Figure 12, respectively. As can be seen from the figure, in the whole
process of tunnel excavation, the displacement of the plan 2 is always slightly smaller than that of the
plan 1, the vertical stress of the plan 2 pipe shed is always greater than plan 1. It shows that plan 2 is
more reasonable, and the pipe sheds arranged in the form of the plan 2 have better bearing capacity.

6. Summary
(1) The stress conditions and constraints of the pipe shed during tunnel excavation are analyzed.
Through the force analysis of the micro-segment of the pipe shed, and the Bernoulli-Euler beam
theory formula is brought into the equilibrium equation of the micro-segment, the control differential
equations of the pipe shed at the vault and the non-arch is obtained.

(2) The MIDAS/GTS NX finite element numerical simulation software was used to simulate the
force deformation model of two large-tube sheds. The deformation law of the pipe shed was obtained
and the deformation mechanism was analyzed.

(3) When excavating the front end of the tunnel, the displacement of the pipe shed is changed only
within a certain range from the front end of the tunnel, and it does not change at a distance; When
excavating to the middle, the displacement rate of pipe shed is very small from a front end of the tunnel to a rear of the excavation face; From the back range of the excavation face to the front part of the excavation, the displacement of pipe shed has changed rapidly, when the rear end face of the tunnel is excavated, the displacement rate of pipe shed at the rear of the excavation face is small.

(4) When the tunnel begins to excavate, the vertical stress drop on the pipe shed only occurs in a part closer to the front end face of the tunnel, and the vertical stress at the pipe shed far from the tunnel excavation face does not change substantially. Excavation to the middle, the vertical stress of the pipe shed at the rear of the tunnel excavation face tends to be fixed. In the certain range in front of the excavation face, the vertical stress of the pipe shed changes sharply. Excavation to the rear end face of the tunnel, excavation face the vertical stress of the rear pipe shed tends to be fixed.

(5) By comparing the displacement and vertical stress of the large pipe sheds of plans 1 and 2, it is concluded that plan 2 is more reasonable and its carrying capacity is better.

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