Research on Waterproof Performance of Prefabricated Utility Tunnel with Different Types of Joints

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Abstract. In the waterproof system of prefabricated utility tunnel, rubber gasket is usually used at the joint of adjacent pipes. The waterproofing effect of prefabricated utility tunnel joint is mostly judged by the field water injection test and the practical effect of former project. In this paper, the finite element software ANSYS is used to carry out the finite element simulation for three types of joint waterproofing of prefabricated utility tunnel. Considering the uneven settlement of utility tunnel foundation, the influence of different staggered joint installation spacing on the waterproofing of the joints is analyzed. Thus, suggestions are provided for the selection of utility tunnel joint. For the prefabricated utility tunnel with side+end face and double-side joint waterproof type, the longitudinal distance between socket joints should be constrained within 3mm after the joint is installed. It is suggested that the end face+side joint waterproof type should be used for the collapsible foundation, and the longitudinal displacement of the control socket and socket should be less than 3mm. For non-collapsible and settled foundation, double-end joint waterproof type or side+end joint waterproof type can be selected.

Keywords. Utility tunnel, rubber gasket, waterproof performance.

1. Introduction
Utility tunnel is a kind of structure built underground to accommodate various kinds of municipal pipelines and their ancillary facilities. It can alleviate the problems of repeated road excavation, dense overhead line network and frequent pipeline accidents in the city, which is conducive to promoting the development of urbanization [1-2]. According to the different construction methods, the utility tunnel includes prefabricated one and the cast-in-place one and joint waterproofing is the key technology for prefabricated utility tunnel. According to the details of tongue and groove, the socket joint type of prefabricated utility tunnel can be divided into different types including end face double rubber ring, side double rubber ring and side+ end face double rubber ring [3]. For types of the double end face joint waterproof and the side+ end face joint waterproof, there is a grouting hole between the two rubber sealing strips, which can be tested by water injection through the grouting hole, and the later leakage can be repaired by grouting. In this paper, three kinds of joint waterproof types of prefabricated utility tunnel is simulated using ANSYS finite element software, and the influence of different installation spacing of staggered joints on waterproof is analyzed.
2. Establishment of Finite Element Model of Rubber Gasket

2.1. Finite Element Model

The model in this paper is shown in figures 1-2.

![Figure 1. Joint waterproof types (mm).](image1)

![Figure 2. Section of rubber strip (mm).](image2)

As the rubber gasket (figure 1c) with the end face+ side waterproof is the same as the rubber 2 in the double side joint waterproof type (figure 3b), the end face+ side waterproof type is not studied separately.

![Figure 3. Finite element model.](image3)

For the rubber gasket, the structure, constraint conditions and stress of the gasket are the same at the joint of adjacent segments along the pipe gallery, therefore, the finite element analysis of rubber strip at the joint of prefabricated utility tunnel can be simplified as a 2D finite element model [4-7]: (1) The single end face trapezoidal finite element model is established for double face waterproof (figure 3a); (2) double side wedge finite element model is established for double side sealing gasket waterproof (figure 3b).

2.2. Element Selection and Mesh Generation

The rubber and concrete elements are plane182. Rubber unit is 0.5 mm and concrete unit is 1 mm.

The elastic modulus of concrete (C40) is 3.25e4 MPa, and that of rubber (hardness is 44) is 1.97 MPa.
2.3. Rubber Constitutive Relation

Mooney Rivlin model is used for the rubber constitutive relation [8-10]:

\[ W = C_1(I_1 - 3) + C_2(I_2 - 2) \]  \hspace{1cm} (1)

where \( W \) is the strain energy density, \( C_1 \) and \( C_2 \) are the coefficients of the material, \( I_1 \) and \( I_2 \) are the first and second strain tensor invariants.

Because of the incompressibility of rubber material, \( \mu = 0.5 \) here. Thus, the elastic modulus \( E_0 \) and shear modulus \( G \) are:

\[ E_0 = 3G = 6(C_1 + C_2) \]  \hspace{1cm} (2)

The elastic modulus \( E_0 \) and hardness \( H_r \) of rubber material is given as in reference:

\[ E_0 = (15.75 + 2.15H_r) / (100 - H_r) \]  \hspace{1cm} (3)

For the values of \( C_1 \) and \( C_2 \), it is assumed that \( C_1/C_2 \) is a constant.

2.4. Failure Criteria of Rubber Gasket

According to the research results of sealing gasket waterproof mechanism, the interface stress less than 1.5MPa specified in the technical code is unreasonable. It is found that the waterproof effect of the sealing gasket of the utility tunnel is generally determined by the on-site water tightness test, and the test water pressure is 0.1MPa. Therefore, in this paper, the rubber gasket waterproof failure criteria is as: when there is no working water pressure, the maximum contact stress and average contact stress of the gasket should be less than 0.8MPa, the maximum contact stress and average contact stress of long-term waterproof gasket should be greater than the design water pressure.

2.5. Contact Model

The contact type is surface contact. The target element is selected as targe169, contact element is selected as conta172, target surface is defined as concrete. The self-contact friction coefficient of rubber is 0.6, and that of rubber and concrete is 0.3.

2.6. Boundary Conditions

The left side of the socket is fixed, the bottom of the model is restricted by the vertical constraint, and the right side of the socket is constrained by displacement. For the side double apron type, the installation joint width is 20 mm, for the side+ end face double rubber ring type and double end face type, the installation joint width is 10 mm.

2.7. Model Validation

The waterproof performance of single hole water swelling adhesive strip was simulated using the Mooney Rivlin model, compared with the compression stress test of urban utility tunnel sealing ring (strip) provided by Sichuan Jiashite Rubber Co., Ltd. (figure 4).

![Figure 4. Model validation](image-url)
3. Finite Element Analysis of Waterproof Effect of Rubber Gasket

By simulating the installation process of rubber gasket, the contact stress of rubber gasket was analyzed. For the waterproof type of end face joint, the trapezoidal gasket is fixed at the groove and bonded with sealant, and the contact stress between the gasket and the left concrete contact surface is analyzed; for the double side wedge finite element model, the rubber gasket is fixed on the left socket working face, and the contact stress between the rubber gasket and the right socket is analyzed.

3.1. Single end Trapezoidal Waterproof Effect Analysis

The compression stress of the rubber strip with trapezoidal cross-section at the end face without working water pressure is shown in figure 4. When the end face gasket reaches its installed compression capacity of 9mm, the compression ratio is 0.428, the average contact stress is 1.01 mpa (the test result is 1.0447 MPa), and the contact pressure and stress diagram of the gasket are shown in figure 5.

![Figure 5. Simulation results of end face rubber gasket with 9 mm compression.](image1)

When the rubber gasket is installed, the holes of rubber strip are not compressed and compacted, and the contact pressure between rubber strip and concrete tends to be large at both ends and small in the middle. This is because of the existence of holes when the rubber strip is compressed, the middle part of the rubber gasket first squeezes the hole, and the rubber material at both ends of the contact surface is always in a dense state with strong deformation resistance capability, and with the rubber on both sides of the hole extruding to the outside, the rubber contact surface on the left and right sides will be “warped”. When the rubber strip is installed, the maximum contact pressure is 5.6 MPa, which meets the requirements of waterproof and sealing.

The influence of water pressure on the waterproof of rubber gasket during its service period was simulated by applying 0.8 MPa working water pressure (parameters in 2.4), shown in figure 6.

![Figure 6. Simulation results of end face rubber gasket with 9 mm compression.](image2)
According to the different opening ratio \((k)\) and compression amount \((l)\), the waterproof performance of rubber cross-section belt under working pressure was simulated by finite element method. The working pressure (water pressure) is 0.8 MPa. The simulation results are shown in table 1.

It can be seen from table 1 that the average contact stress and maximum contact pressure of rubber gasket under working water pressure are greater than those under no working pressure, that is, a certain working water pressure can improve the sealing and waterproof performance of rubber gasket. Therefore, if the water pressure is less than 0.8 MPa, the existence of water pressure can be ignored when designing the rubber gasket at the joint of adjacent segments.

**Table 1.** Contact stress of single hole rubber gasket before and after working pressure.

| Opening ratio \(k\) | Amount of compression/mm | Average contact stress Under no working water pressure | Maximum contact stress Under no working water pressure | Average contact stress Under working water pressure | Maximum contact stress Under working water pressure |
|---------------------|--------------------------|------------------------------------------------------|------------------------------------------------------|---------------------------------------------------|---------------------------------------------------|
| 0.05                 | 5.6                      | 1.534                                                | 9.16                                                 | 1.760                                             | 9.87                                              |
| 0.1                  | 6.8                      | 1.520                                                | 10.24                                                | 1.800                                             | 10.88                                             |
| 0.15                 | 8.2                      | 1.566                                                | 12.06                                                | 2.400                                             | 14.11                                             |
| 0.2                  | 9                        | 1.540                                                | 12.81                                                | 1.985                                             | 13.00                                             |
| 0.25                 | 9.8                      | 1.500                                                | 13.98                                                | 1.710                                             | 13.69                                             |

3.2. Verification of Double Side Wedge Waterproof

It can be seen from section 3.1 that the working water pressure can increase the contact stress of the gasket. For wedge-shaped rubber gasket, because it is difficult to determine the water pressure action surface, this paper simulates the contact stress of rubber gasket under the condition of no working water pressure, and then judges its waterproof effect. If there is no working water pressure, the rubber gasket can meet the waterproof sealing requirements, then under the working water pressure condition, the sealing gasket waterproof can also meet the waterproof requirements.

The finite element simulation results of double side joint waterproof type are shown in table 2.

**Table 2.** Contact stress simulation results.

| Joint width/mm | Average contact stress /MPa | Maximum contact stress /MPa |
|----------------|----------------------------|----------------------------|
| Rubber gasket 1 | Rubber gasket 2             | Rubber gasket 1            | Rubber gasket 2 |
| 50             | 0                          | 0.12                       | 0.24           |
| 45             | 0.43                       | 0.67                       | 0.53           | 0.99           |
| 40             | 0.65                       | 1.3                        | 0.92           | 1.53           |
| 35             | 0.96                       | 1.79                       | 1.33           | 2.27           |
| 30             | 1.18                       | 2.09                       | 1.59           | 3.18           |
| 25             | 1.21                       | 1.67                       | 1.75           | 3.5            |
| 20             | 1.20                       | 1.68                       | 2.04           | 2.87           |
It can be concluded from table 2 and figure 7:

1) When the utility tunnel joint is installed (with joint width 20 mm), the average contact stress and maximum contact stress of the two rubber gaskets are both greater than 0.8 MPa, meeting the short-term waterproof requirements. There is no leakage during the field water injection test.

2) For the double side joint waterproof type, the maximum Von Mises stress appears at the contact surface between rubber 2 and the socket after the rubber strip is installed. It can be seen that the deformation of rubber 2 is larger, so the Von Mises stress of rubber 2 is larger than that of rubber 1.

3) With the decrease of joint width, the average contact stress and maximum contact stress of rubber 1 increased, while that of rubber 2 increased first and then decreased.

3.3. Verification of Waterproof Effect of Sockets with Staggered Joint

The special collapsibility of loess causes uneven settlement of adjacent segments of utility tunnel. According to Chinese code for construction and acceptance of shield tunnelling method (GB 50446-2017), the allowable height difference of transverse segment is 5mm, and that of longitudinal segment is 6mm. In this paper, the influence of vertical staggered joint of socket and spigot on waterproof effect of sealing strip is studied. Considering the adverse working condition of socket and spigot, the fixed constraint was applied to the socket, and the vertical displacement of 1 mm, 2 mm, 3 mm, 4 mm, 5 mm, 6 mm was applied to the socket. For the waterproof type of double end face joint, the influence of staggered installation of socket and spigot on the waterproof of sealing gasket is not considered. The results of finite element simulation are shown in figures 8-9.

(a) Average contact stress of rubber gasket
(b) Maximum contact stress of rubber gasket

Figure 7. Simulation results of wedge-shaped rubber gasket.

Figure 8. Simulation results of rubber 1 contact stress.
(a) Average contact stress of rubber gasket  
(b) Maximum contact stress of rubber gasket

Figure 9. Observation of rubber 2 contact stress simulation results.

It can be seen from figures 8-9 that:

1) With the decrease of joint width, the average contact stress of rubber increases at first and then tends to be stable. The maximum contact stress increases at first and then decreases. When the joint width is 30mm, the maximum joint stress reaches the maximum value. Therefore, the rubber assembly force and the assembly force required after installation should be calculated to determine the maximum assembly force to install the rubber strip.

2) The average contact stress and maximum contact stress of rubber 1 and rubber 2 decrease with the increase of staggered joint distance. When the joint width is 20 mm and the installation staggered joint is 3 mm, the maximum contact stress of rubber 1 is 0.81 MPa, and the maximum contact stress of rubber 2 is 0.95 MPa, which are both greater than the working water pressure 0.8 MPa, which can meet the short-term waterproof requirements. When the installation staggered joint space is greater than 3 mm, it does not meet the waterproof requirements.

The simulation results show that the maximum Von Mises stress of rubber 2 is greater than that of rubber 1 after the utility tunnel segment is installed. Therefore, the maximum Von Mises stress of rubber 2 after segment installation is studied. The simulation results are shown in table 3.

Table 3. Simulation results of maximum von Mises stress of rubber 2 (MPa).

| Staggered joint/mm | 0  | 1  | 2  | 3  | 4  | 5  | 6  |
|--------------------|----|----|----|----|----|----|----|
| Maximum Von Mises stress | 7.37 | 4.81 | 2.82 | 2.71 | 2.30 | 1.73 | 1.25 |

It can be found from table 3 that the maximum Von Mises stress of rubber 2 decreases with the increase of installation distance of staggered joints after the pipe gallery segment is installed. The Von Mises stress reflects the difference of principal stresses on the section of sealing ring. The larger the value is, the lower the stiffness of rubber will be and the therefore cracks appear. In this simulation, the distance between the socket and socket of concrete at the rubber part is designed to be 16mm. For the waterproof type of double side rubber joint, when the installation distance of staggered joint is greater than 3mm, the sealing gasket cannot meet the waterproof requirements.

4. Conclusion

In this paper, finite element software ANSYS is used to simulate three kinds of waterproof joint types of prefabricated utility tunnel. Focus on the uneven settlement of utility tunnel foundation, the influence of different installation space of staggered joints on waterproof of utility tunnel joint is analyzed, so as to provide suggestions for joint type selection. The conclusions are as follows:

1) For the double side joint waterproof type and the end+ side joint waterproof type, with the decrease of the longitudinal distance between the spigot and the socket (staggered joint space), the waterproof performance of the rubber gasket becomes better, and the maximum longitudinal distance between the spigot and the socket can reach 19 mm. For the waterproof type of double end joint, the
The influence of staggered joint installation is not considered. For the double end joint waterproof type and the end+ side joint waterproof type, grouting holes are set. After the sealing gasket is installed, the water tightness test can be carried out through the grouting hole to test the waterproof effect of the rubber gasket, and the water leakage repair can be carried out through grouting hole during the service period of the rubber gasket. Therefore, for the collapsible foundation, it is recommended to use the waterproof type of end face+ side joint, and the longitudinal displacement between the spigot and socket should be less than 3 mm. For the foundation without collapsibility, double end face joint waterproof type or side+ end face joint waterproof type can be applied.

(2) When the design water pressure of utility tunnel is less than 0.8 MPa, the working water pressure can increase the contact stress of the gasket, i.e., the waterproof performance of the gasket can be improved.

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References
[1] Xue W C, Hu X and Wang H D 2007 Application and research progress of utility tunnel Special Structure 24(1) 96-99.
[2] Wang H D and Wang M 2004 Overview of multipurpose pipe line and channel Shanghai Construction Technology 3(1) 37-39.
[3] Yan L 2017 Development status of prefabricated assembly utility tunnel and discussion on water resistance and sealing performance of joint Concrete and Cement Products 249(1) 31-34.
[4] Tan J, Yang W M, Ding Y M, et al. 2006 Finite element analysis of the sealing performance of O-ring seal structure Lubrication Engineering 181(9) 65-69.
[5] Yang C M and Xie Y J 2010 Ansys analysis of the sealing performance of rubber O-sealing ring China Elastomerics 20(3) 49-52.
[6] Tan J, Yang W M, Ding Y M, et al. 2007 Finite element analysis of rectangular rubber seals Lubrication Engineering 32(2) 36-39.
[7] Liu J, Qiu X Q, Bo W S, et al. 2010 Numerical Analysis on the maximum contact pressure of Rubber O-ring Lubrication Engineering 35(1) 41-44.
[8] Liu M, Wang Q Q and Wang G Q 2011 Determination of material parameters of moone rivlin model of rubber Rubber Industry 58(4) 241-245.
[9] Zheng M J, Wang W J, Chen Z G, et al. 2003 Determination of mechanical property constants of Mooney Rivlin model for rubber Rubber Industry 50(8) 462-465.
[10] Zhang L G, Li Z G and Ma X Q 2018 Parametric properties of Mooney Rivlin hyperelastic constitutive model for rubber Noise and Vibration Control 38(Z1) 427-430.