Bending mechanics model and value of transverse joints in precast prestressed utility tunnel

Pengyu Wang*, Shuhong Wang*, Muhammad Israr Khan* and Chengjin Zhu*

*School of Resources and Civil Engineering, Northeastern University, Shenyang City, China

ABSTRACT

Joints lead to the uneven distribution of structural rigidity of a precast prestressed utility tunnel (PPUT) and changes in internal forces and deformation. From research perspective, bending stiffness is important as an important indicator to evaluate the performance of PPUT joints and an important factor to evaluate the overall mechanical properties of PPUT structures. After considering the actual structural form of a transverse joint section and the characteristics of force deformation, a mechanical model that can characterize the joint section from force to failure and the corresponding analytical expressions were established using the internal force balance and deformation coordination conditions. A sensitivity analysis of the factors affecting the bending stiffness of joints was carried out using numerical simulation methods. The theoretical calculation results were compared with the numerical simulation results. Finally, according to the obtained trend of bending stiffness change, a two-stage bending stiffness method is proposed for the transverse joints of PPUT. The results of the study provide a reference for the design and theoretical analysis of PPUT.

1. Introduction

In recent years, with the vigorous development of urban underground space in China, the maintenance, expansion, and renovation of municipal pipelines have led to repeated excavation of urban roads. This causes urban traffic congestion and becomes an important factor for constraining urban infrastructure construction and sustainable green environmental protection. To solve this problem, China has constructed utility tunnels in many cities (Canto-Perello and Curiel-Esparza 2013).

A utility tunnel is a complex tunnel laid under a city road by integrating various municipal pipelines such as water supply, drainage, communications, electricity, and heat, thus achieving “unified planning and unified management of various municipal pipelines” (Figure 1) and effectively promoting the sharing and comprehensive utilization of underground space resources (Hunt, Nash, and Rogers 2014; Llobb, Blanpain, and Buyle-Bodin 2004).

At present, the construction methods for a utility tunnel mainly include cast-in-place method and prefabrication method (Figure 2) (Chen-Jun, Li, and Shi 2012). Among them, the precast prestressed municipal tunnel (PPMT) is the most widely used construction technology in the prefabrication method (Perello and Curiel-Esparza 2007). PPMT technology has achieved remarkable construction achievements in the utility tunnel project of Shanghai World Expo Park. PPMT technology has the advantages of high efficiency, low cost, and environmental protection. A PPMT can be divided into prefabricated segment utility tunnel with only longitudinal joints and prefabricated municipal tunnel with both longitudinal and transverse joints (Figure 3) (Julian Canto, Curiel-Esparza, and Calvo 2013). The volume and weight of each section of utility tunnel are relatively large. To ensure the convenience of utility tunnel transportation and on-site assembly, the width of each section of utility tunnel is generally controlled between 1.5 m and 2 m, thus forming a lot of joints (Wei-chen 2002).

The joints significantly affect the performance of utility tunnel (Yoo and Kim 2003). The presence of joints leads to the uneven distribution of utility tunnel’s structural stiffness, internal forces, and deformation change. Therefore, the joints are important from research perspective as a key part of PPMT (Li Yu-Jie 2012; Zhang Jian-Gang 2013).

Bending stiffness is not only an important index to measure the performance of joint, but also an important factor in evaluating the overall mechanical properties of utility tunnel (WANG Peng-yu, Li, and Jie Ru La 2018; Wang Shu-Hong et al., 2018). Tongji University has conducted full-scale tests on the bending mechanical properties of longitudinal joints of PPMT, whereas transverse joints have not been studied yet (Xue Wei-Chen et al., 2009). Theoretical analysis and numerical
Simulation methods were used in this study to evaluate the bending stiffness of transverse joints.

2. Transverse joint bending stiffness calculation model

2.1. Joint construction

The construction form and size of a transverse joint are shown in Figure 4. The longitudinal joints are connected using prestressed tendons, and the transverse joints are connected using high-strength bolts. Joint section reserved seam to ensure assembly accuracy. To satisfy the waterproof requirement at the joints, rubber strips are inflated in the reserved grooves. Literature data were used to determine the depth and width of reserved grooves and preloading of high-strength bolts.

2.2. Basic assumptions

The lateral joints are deformed under the action of upper earth pressure and lateral earth pressure as shown in Figure 5.

According to the force characteristics and specific configuration of transverse joints, the following assumptions are made:

- The relative rotation of transverse joints is the main cause of deformation of side walls of a utility tunnel as shown in Figure 5. Among them, the tensile deformation of high-strength bolts and the compression deformation of concrete in the compressed area of joint section cause the relative rotation of joint.
- When the joint section is not open, the entire section is subjected to pressure and satisfies the flat section assumption. When the joint section opens, both the sections of tensioned concrete and compression concrete remain flat, confirming the flat section assumption.

Figure 1. Urban utility tunnel.

Figure 2. Urban utility tunnel construction methods.

Figure 3. Joint form of precast prestressed utility tunnel.

Simulation methods were used in this study to evaluate the bending stiffness of transverse joints.
3. Theoretical calculation of bending stiffness of transverse joints

3.1. Force of transverse joints

First, the transverse joint is subjected to the tightening force of bolt. The bolt tightening force has two functions: (i) to fix the joint so that the segment pieces do not move relatively; (ii) to provide the pressure needed for the seal ring to close the joint. Second, after the foundation pit is backfilled, the utility tunnel joint is also subjected to the surrounding earth pressure.

The fastening force of high-strength bolt is equivalent to a uniform distribution of compressive stress along the cross-section of joint. The upper earth pressure is equivalent to pressure load $N$, and the lateral earth pressure is equivalent to bending moment $M$, thus forming a transverse joint force diagram of the utility tunnel, as shown in Figure 6.

According to the change of force, the deformation of transverse joint section of utility tunnel can be divided into the following three situations.

3.2. Opening height of joint section is lower than the bolt position

When the opening height $h_1 < h_2$, the deformation of joint section is shown in Figure 7. The opening height $h_1$, the height of compressed zone $h_3$, and the thickness of joint have the following relationship.

$$
\frac{h_2}{h_1} = \frac{h_3}{h_1} = \frac{h \cos \frac{\theta}{2} - h_1}{h_1}
$$

$$
h_1 + h_3 = h \cos \frac{\theta}{2}
$$

The compression of concrete at the outer edge of compression zone of joint section can be expressed as follows:

$$
\delta_2 = 2h_3 \tan \frac{\theta}{2} = \theta \left( h \cos \frac{\theta}{2} - h_1 \right)
$$

Because the corners of joint sections are small, $\tan \theta = \theta$ can be approximated. According to the assumption, the deformation of outer edge of concrete

![Figure 4](image_url)

Figure 4. Construction of transverse joints.

![Figure 5](image_url)

Figure 5. Sidewall deformation diagram.
compression zone on one side of the joint section can be expressed as follows:

\[ \delta_2 = \varepsilon_2 \ell_{ef} \]  

(13)

According to the flat section assumption, the following relationship can be obtained:

\[ \frac{\varepsilon_2}{h \cos \frac{\theta}{2} - h_1} = \frac{\varepsilon_y}{h_y - h_1} \]  

(14)

According to the force balance of the joint section (Figure 8), the following relationship can be obtained:

\[ \sum N = 0 \quad nT + N = F_1 \]  

(15)

\[ \sum M = 0 \]

\[ M = nT \left( \frac{h}{2} - h_2 \right) \cos \frac{\theta}{2} + F_1 \left( y_1 - \frac{h}{2} \right) \cos \frac{\theta}{2} \]  

(16)

\[ F_1 = \int_{h_1}^{h_3} \sigma_1(y) b dy \]  

(17)

\[ y_1 = \int_{h_1}^{h_3} \frac{\sigma_1(y)}{h \cos \frac{\theta}{2}} \cos \frac{\theta}{2} \]  

(18)

In the formula, \( \varepsilon_2 \) is the strain of concrete at the outer edge of compression zone on one side of joint section. \( \varepsilon_y \) is the strain of concrete when the compression area of joint section is at the \( y \) height position. \( F_1 \) is the resistance generated by concrete in the compression zone. \( y_1 \) is the centroid position of concrete in the compression zone of joint section; \( b \) represents the width of each section of utility tunnel; \( E_c \) represents the elastic modulus of precast concrete. \( \delta_1 \) is the maximum amount of opening of joint section; \( \delta_2 \) is the maximum amount of compression of joint section; \( h_2 \) is the distance from the high-strength bolt to the inside of side wall of utility tunnel.

Finally, the bending stiffness of joint at this stage can be obtained using equation (19).

\[ K_0 = \frac{M}{\theta} \]  

(19)

3.3. Opening height of joint section is higher than the bolt position

When the opening height \( h_2 < h_1 < h \), the deformation of joint section is shown in Figure 9. According to the
flat section assumption, the following relationship can be obtained:

\[
\frac{\Delta l_b}{\delta_1} = \frac{h_1 - h_2 \cos \frac{\theta}{2}}{h_1} \quad (20)
\]

\[
\frac{\epsilon_2}{h \cos \frac{\theta}{2} - h_1} = \frac{\epsilon_3}{h_1 - h_2 \cos \frac{\theta}{2}} \quad (21)
\]

where \( \epsilon_3 \) is the strain of high-strength bolt when the opening height of joint section is \( h_1 \). According to Eq. 20, the force of high-strength bolt can be obtained as follows:

\[
T_b = \frac{\delta_1 (h_1 - h_2 \cos \frac{\theta}{2})}{h_1 l_b} E_b A_b
\]

According to the force balance of joint section (Figure 10), the following relationship can be obtained:

\[
\sum N = 0F_1 = n(T + T_b) + N \quad (23)
\]

\[
\sum M = 0
\]
\[ M = n(T + T_b) \left( \frac{h}{2} - h_2 \right) \cos \frac{\theta}{2} + F_1 \left( \gamma_1 - \frac{h}{2} \right) \cos \frac{\theta}{2} \]  

(24)

Finally, the bending stiffness of joint at this stage can be obtained using Formula (19).

### 3.4. Crushing of joint section concrete and yielding of bolts

When the outer edge of compression zone concrete of joint section reaches the ultimate compressive strain, the joint section is collapsed. At this point, the force of joint section is shown in Figure 11, and the following relationship can be obtained:

\[ \varepsilon_2 = \varepsilon_{cu} \]  

(25)

\( \varepsilon_{cu} \) is the ultimate compressive strain of concrete.

The load continues to increase until the high-strength bolt yields. At this time, a part of the concrete of joint section has already stopped working, and the joint is unstable. The force of joint section is shown in Figure 12.

\[ T_b = f_b A_b \]  

(27)

where \( f_b \) is the yield stress of high-strength bolt; \( \Delta h \) is the height of concrete that stopped working.

According to the above formula, the values of \( \theta \) and \( h_1 \) can be obtained. Finally, the bending stiffness of joint at this stage can be obtained using Formula (19).

---

**Figure 10.** Strains after the bolts bearing force.

**Figure 11.** Strains at concrete beginning crushing.
4. Numerical simulation of transverse joints

4.1. Constitutive relationship of materials

ABAQUS software was used for numerical simulation. When a numerical model for transverse joints is established, it is assumed that the prefabricated utility tunnel is an isotropic homogeneous material, and the difference in material can be ignored. Precast concrete is simulated by a solid element, and the constitutive relationship is based on the Hognestad constitutive model. The rising ascending section of the model is a quadratic parabola, and the falling descending section of the model is an oblique straight line. The peak stress corresponds to a strain of 0.002; the ultimate compressive strain is 0.0038; the compressive strength is 28 MPa; the tensile strength is 2.6 MPa; the Poisson’s ratio is 0.2 (Figure 13).

The high-strength bolts were simulated using the Beam unit, a good model for simulating an elongated structure. The constitutive relationship uses the bilinear isotropic strengthening model, reflecting the characteristic that the stress can still grow after the bolt yields. The high-strength bolt has yield strength of 480 MPa and an ultimate strength of 600 MPa. The constitutive relationship of the steel uses the ideal elastoplastic two-fold line model. The steel is linear elastic before yielding, and the strength does not change after yielding. The yield stress of steel is 436 MPa, and the modulus of elasticity is 198 GPa.

4.2. Defining constraints

A 3D numerical model of the transverse joint of utility tunnel is shown in Figure 14. The model is made of two standard segments joined by bolts. The initial strain applied to the high-strength bolts was used to simulate the anchoring force of high-strength bolts during an actual construction. To prevent the local damage of concrete, steel gaskets with a thickness of 6 mm were set as the support. The steel gasket and segment are bound by Tie unit. The constraint of steel gasket are \( U_1 = 0, U_2 = 0, \) and \( U_3 = 0 \), that is adding the hinge constraint as the boundary condition. Constraint was defined in the integration module, and embedded was selected for establishing the constraint between the steel and concrete. The contact between two transverse joints of precast segments was defined as the surface-to-surface contact, defined as a hard contact in the normal and defined as the friction in the tangential (Chen-Jun, Li, and Shi 2012). The penalty function algorithm was selected, and a friction coefficient of 0.2 was taken. The same definition form was used between the high-strength bolt and hole wall; hard contact was in the normal and tangential directions. A penalty function was used to define friction with a friction coefficient of 0.3 (Choi, Choi, and Choi 2013).
4.3. Loading method

According to the force characteristics of joint section in actual engineering, the upper earth pressure load $N$ was simulated by applying a horizontal load $F_X$, and the bending moment $M$ generated by the lateral earth pressure was simulated by applying a vertical load. The numerical model under load is shown in Figure 15.

4.4. Analysis of factors affecting bending stiffness

4.4.1. Joint thickness

The horizontal load $N$ is 200 kN; the high-strength bolt is 0.1 h from the inner side of side wall plate; the initial tightening force $F$ of the bolt is 40 kN. When the above parameters are unchanged, the joint thickness is 0.25 m, 0.30 m, 0.35 m, and 0.4 m; the curve of $M/\theta$ of joint section is shown in Figure 16.

Figure 16 shows that when the thickness of transverse joint is increased from 0.25 m to 0.45 m, the bending stiffness of joint section is doubled. Therefore, in the design of utility tunnel, it is necessary to consider the thickness of joint.

4.4.2. Bolt location

The position of bolt of transverse joint section of a prefabricated prestressed utility tunnel is shown in Figure 16. Generally, the bolts are located close to the inner side of joint section. The horizontal load $N$ is taken as 100 kN and 200 kN. The initial tightening force $F$ of high-strength bolt is 40 kN, and the thickness $t$ of joint is 0.3 m. When the bolt is 0.05 m, 0.1 m, and 0.15 m away from the inner side of joint section, the curve of $M/\theta$ of the joint is shown in Figure 17.

Figure 18 shows that when the position of bolt is closer to the inner side of joint section, the bolt is more effective in promoting the stability of joint section, because when the bolt moves inward, the bolt’s ability to restrain the joint opening is improved, and the time for the joint to reach a stable state is shortened, thus improving the bending stiffness of joint.

At the same time, it was also found that when the horizontal load $N$ increases, the effect of bolt position on the bending stiffness of joint is gradually reduced, because an increase in the horizontal load increases the restraining ability of joint section rotation, thereby reducing the effect of bolt position.

---

**Figure 13.** Precast concrete constitutive relationship.

**Figure 14.** Transverse joint 3D model.
4.4.3. Bolt preload

In the numerical simulation, the initial tightening force was obtained by applying the initial strain to the bolts. The bolt section stress is $\sigma = F/S$, and the corresponding strain is $\varepsilon = \sigma/E$, so that the initial preload is $F = \varepsilon ES$ (Sun Wen-Hao and Lan 2008). Among them and indicate the elastic modulus and cross-sectional area of the bolt (Jiang Hong-Sheng 2004), respectively. The variation of $M - \theta$ was analysed when the preload force $F$ was 20 kN, 40 kN, 60 kN, 80 kN, and 100 kN.

Figure 19 shows that the bolt fastening force slightly affects the bending stiffness of transverse joint. When the initial tightening force of bolt is increased, the joint section angle is slightly reduced, and the bending stiffness is improved to some extent. Because the bolt tightening force forms a partial eccentric pressure on...
the joint section during the deformation of joint section, the pressing action of pressure on the joint section causes the joint to remain in a closed state.

Therefore, the bolt tightening force is larger, and the corner angle is smaller when the joint section reaches a steady state. With the increase in axial force, the restraining ability of joint rotation is gradually increased, weakening the effect of bolt fastening force on joints. Overall, the bolt tightening force has less effect on the bending stiffness of transverse joint.

5. Comparison of two calculation models

When the bending stiffness of joint is calculated using the theoretical model of bending stiffness of transverse joint of utility tunnel, the horizontal loads $N$ are taken as 100 kN and 200 kN. Left is taken as 0.5 times, 1.0 times, and 1.5 times of the joint thickness, and the bolt tightening force is taken as 40 kN. Other calculation parameters are shown in Table 1.

5.1. Maximum opening comparison

A curve of maximum opening amount of transverse joint section as a function of bending moment was obtained by numerical simulation and theoretical calculation, as shown in Figure 20.

Figure 20 shows that when the bending moment of transverse joint section increases, the maximum opening amount of section shows a nonlinear growth trend, which first increases slowly and then increases rapidly. When the bending moment is the same, the larger the horizontal load $N$, the smaller the maximum opening amount of joint section.

The maximum opening amount of joint section should satisfy the waterproof design requirement (less than 3 mm). Therefore, according to the variation curve of Figure 20, it can be concluded that the maximum bending moment that the joint section can withstand must be less than 300, thus providing a reference for the waterproof design of utility tunnel.

When the bending moment is small, the theoretical calculation results are consistent with the numerical simulation results. At this stage, the constitutive model of concrete is more consistent with the actual elastic state of concrete. When the bending moment exceeds 250 kN/m, the theoretical calculation result is larger than the numerical simulation result. At this time, the concrete in the compression area of joint section shows a nonelastic state.
Compared with the left taken as 1 H and 1.5 H, the theoretical calculation result is closer to the numerical simulation result when the left is taken as 0.5 H.

### 5.2. Bolt force comparison

Through numerical simulation and theoretical calculation, a curve of the force of high-strength bolt with the opening height of joint was obtained, as shown in Figure 21.

The trend of curves obtained using the two calculation methods is consistent: When the opening height of joint section is lower than the bolt position, the bolt is almost unstressed. When the opening height is higher than the bolt position, the force of bolt shows an approximately linear increasing trend with the increase in opening height, indicating that the high-strength bolt is in the state of linear elasticity.

### 5.3. Open height comparison

Through numerical simulation and theoretical calculation, a curve of opening height of joint with bending moment was obtained, as shown in Figure 22.

The trend of curves obtained using the two calculation methods is consistent: The opening height of joint section increases with the increase in bending moment. When the bending moment is small, the opening height of joint section increases linearly; when the bending moment is more than 200 kN-m, the opening height increases slowly, because the opening height exceeds the position of high-strength bolt at this time, and the joint section is subjected to the pulling force of bolt.

When the bending moment is the same, the opening height of joint section decreases with the increase in horizontal load N, indicating that the horizontal load has a restraining effect on the opening of joint section.

### 5.4. Comparison of bending stiffness

Through numerical simulation and theoretical calculation, a curve of bending stiffness of transverse joint was obtained, as shown in Figure 23.

When the bending moment is small, the bending stiffness tends to increase linearly. As the bending
moment increases, the pressure on the concrete outside the joint section increases; the concrete is further compressed; the compression stiffness increases; the deformation gradually decreases. The pressure on the concrete inside the joint section is continuously reduced; the compression stiffness is continuously reduced. The pressure on the concrete inside the joint section is continuously reduced; the compression stiffness is continuously reduced.

Figure 20. Comparison of joint maximum opening amount.

Figure 21. Comparison of bolt stresses.

Figure 22. Comparison of opening height.
reduced and gradually enters the relaxation compression stage, leading to an increase in the pressure difference between the inner and outer sides.

The recovery rate of compression deformation is greater than the rate of decrease of deformation increment of the pressure increase part, resulting in a continuous increase in the rotation angle at the joint, gradual separation of joint cross-section, and the formation of compression zone and open zone.

Then, the bolts are subjected to tensile forces and the concrete is under pressure. Both of them jointly resisted the external load, and the final joint section gradually became stable.

With the increase in bending moment, the concrete in the compression zone and compressed section of the joint section is crushed, the bolts yield, and the joint stiffness decreases, thus resulting in a rapid increase in the joint angle.

A comprehensive comparison and analysis of calculation results of the two models showed that when the influencing depth of the concrete compressive strain in the compression area of joint section is 1.0 H and 1.5 H in the theoretical calculation model, the theoretical calculation results show a large deviation from the numerical simulation results. When Left = 0.5H, the comparison results of the two models are consistent. Therefore, Left is recommended to be (take) 0.5 H in the theoretical calculation of bending stiffness of transverse joint.

When Left = 0.5H, the results of the two models agree well with each other. Therefore, it is recommended that Left be 0.5 H in the theoretical calculation model for determining the bending stiffness of joints.

From the comparison of the results of theoretical calculation model and numerical model, it can be observed that although the two joint models show similar changes, there are still some differences. The comprehensive analysis has the following reasons:

The numerical model is a spatial three-dimensional model that considers the longitudinal space of the gallery, thereby improving the flexural performance of joint. The theoretical calculation model is a planar two-dimensional model, ignoring the effect of joint space effect on the mechanical properties; there are differences in the stress distribution patterns of joint sections of theoretical and numerical models.

In the theoretical calculation model, the deformation of the outermost concrete in the compression zone of joint section is approximated, inevitably different from the state of numerical model.

In general, although the theoretical and numerical models of transverse joints all have their own assumptions and equivalent processes leading to differences in the calculation results, both the models reflect the changes in the bending stiffness of joints.

6. Experimental study on the stress performance of transverse joints

6.1. Test piece design

The mechanical properties of transverse joints of bolted prefabricated utility tunnel were evaluated by 1: 1 full scale model test. The test piece in the model was spliced using two prefabricated segments by fastening 10.9 stage M30 high-strength bolts. The cross-sectional dimension is shown in Figure 4. 10.9-10 indicates that the bolt has a tensile strength of 1000 MPa, and 9 indicates that the ratio of yield strength to tensile strength is 0.9. Thus, the yield strength of bolt is 900 MPa. M30 indicates that the bolt has a diameter of 30 mm. Bolts made of low-carbon alloy steel or medium-carbon steel and subjected to heat treatment (quenching and tempering) are known as high-strength bolts, and the remaining are collectively referred to as ordinary bolts (Todut, Dan, and Stoian 2014). Figure 24 shows a reinforcement drawing of the test piece. The
strength grade and waterproof grade of the test piece concrete are C40 and S6, respectively. A groove is reserved at the abutted seam of the test piece joint, and a 821-BF type water swelling rubber is pasted. In the theoretical calculation model, the effect of water swelling rubber is neglected. Other experimental parameters are shown in Table 2.

### 6.2. Loading method and test content

The test loading can be divided into two stages: tightening the bolt and applying the sidewall load. Sidewall loading is performed by applying equivalent monotonic static loading synchronously to the four sidewalls of the overall structure test pieces, as shown in Figure 25. The test simulates multiple loads of the overall structure, including standard load conditions, design load conditions, 1.5 times design load conditions, two times design load conditions, three times design load conditions, and ultimate failure. According to the design requirements of a utility tunnel structure, the sidewall loads $P$ of the overall structural test piece under standard load conditions and design load conditions are 50 kN and 80 kN.

![Figure 24. The reinforcement drawing of the test piece.](image)

**Table 2. Test parameters.**

| Test parameters | $h_1$(mm) | $h$(mm) | $A_b$(mm) | $f_b$(N/mm²) | $E_b(10^5)$ N/mm² | $l_b$(mm) | $E_c(10^4)$ N/mm² |
|-----------------|-----------|---------|-----------|--------------|-------------------|-----------|------------------|
| Joint section   | 100       | 300     | 706       | 903          | 2.01              | 500       | 3.52             |

![Figure 25. Install strain gauges and loading installation.](image)
respectively. In the test loading device, a 10,000 kN microcomputer was used to control the electrohydraulic servo multifunction testing machine system. Notably, because of a larger size of the test piece, the overall structural test piece was rotated by 90° in the test to satisfy the space size requirement of testing machine. The testing content of overall structural stress performance test mainly includes the following: Strain in high-strength bolts and ordinary steel bars and the opening amount of beam of transverse joint and seam corner, including the mid-span deflection of sidewall of beam (Chen et al. 2017).

6.3. Failure process of test piece

First of all, it is required to tighten the bolts, and then completely seal the joint of test piece before applying load on the side wall. In the process of applying load on the side wall, the test piece experienced three stages: cracking, yielding and ultimate failure. During this process, the cracks first appeared on the outer edge section of the haunched area at the end of the cast-in-place side wall of the test piece, and the joint seam was still closed at this moment. With the increase of the load, the cracking area gradually extended to the middle of the side wall span when the joint seam gradually opened. When \( P \) (the load on side) reached two times of the design load, the joint seam opened for about 3 mm; when \( P \) reached three times of the design load, the tensile longitudinal bar at the end of the test piece yielded and the joint seam opened for 8 mm. With the increase of \( P \), the concrete in the compression zone of the joint peeled off; meanwhile the overall deformation of the structure increased rapidly and reached the ultimate limit state. At this time, the bolt strain was about 80% of the yield strain, and the opening of joint seam is about 24 mm.

6.4. Analysis and comparison of results

To verify the accuracy of the established theoretical calculation model of utility tunnel joint, the test results were compared with the theoretical calculation results, as shown in Table 3, where indicates the angle of opening at joint beam, and indicates the bending moment at the joint. The result of theoretical calculation is consistent with the experimental result as a whole, indicating that the theoretical calculation model and method developed for determining the bending stiffness of transverse joint of prefabricated utility tunnel can accurately describe the deformation and internal force state of joint during the whole process of stress (Chen et al. 2019).

There are two main reasons for the error between the experimental and theoretical values: First, the members in the test are larger in size and difficult to be controlled, and errors will inevitably occur in the assembly and measurement. Manufacturing errors are present in the flatness and reserved groove size at the joint. As the opening width at the joint increases, the error between the theoretical experimental values decreases, mainly because the joint is subjected to more uniform force when the load increases, and the actual force at the joint can better comply with the assumption of theoretical model.

6.5. Two-stage value method for bending stiffness of transverse joints

Figure 26 shows that the bending stiffness of joint is not fixed during the change in the bending moment of joint (Zhang and Fang Ruo-Quan 2017). Therefore, it is obviously unreasonable to take a fixed value of bending stiffness in the mechanical calculation of tube gallery. According to the curve obtained in this study, the bending stiffness is revalued (Feng Kun and Ming-Qing 2016).

### Table 3. Comparison of theoretical calculation results and test results.

| Force stage | Theoretical values | Experimental values | Theoretical values/experimental values |
|-------------|--------------------|---------------------|----------------------------------------|
| Before yielding \( \theta = 0.0004 \) M/(kN·m) | 35.8 | 28.7 | 1.25 |
| High-strength bolt strain \( \times 10^{-3} \) | 2.632 | 2.096 | 1.26 |
| Maximum crack width/mm | 0.52 | 0.54 | 0.96 |
| High-strength bolt strain \( \times 10^{-3} \) | 57.5 | 48.1 | 1.20 |
| Maximum crack width/mm | 3.366 | 2.948 | 1.15 |
| \( \theta = 0.005 \) M/(kN·m) | 74.2 | 62.8 | 1.18 |
| High-strength bolt strain \( \times 10^{-3} \) | 4.269 | 3.625 | 1.17 |
| Maximum crack width/mm | 3.34 | 3.16 | 1.06 |
| \( \theta = 0.012 \) M/(kN·m) | 7.07 | 6.42 | 1.10 |
| High-strength bolt strain \( \times 10^{-3} \) | 4.812 | 4.263 | 1.13 |
| Maximum crack width/mm | 12.41 | 10.25 | 1.21 |
| \( \theta = 0.02 \) M/(kN·m) | 8.01 | 7.56 | 1.06 |
| High-strength bolt strain \( \times 10^{-3} \) | 6.274 | 5.631 | 1.12 |
| Maximum crack width/mm | 15.28 | 16.36 | 0.93 |
| \( \theta = 0.03 \) M/(kN·m) | 85.7 | 81.2 | 1.03 |
| High-strength bolt strain \( \times 10^{-3} \) | 7.265 | 6.948 | 1.05 |
| Maximum crack width/mm | 25.96 | 23.62 | 1.10 |
| \( \theta = 0.04 \) M/(kN·m) | 87.2 | 91.6 | 0.95 |

Ultimate bearing capacity
When the bending moment of joint section is small, the section angle of joint is small. As the bending moment increases, the amount of opening of joint section increases, the concrete in the compression zone collapses, and the bolt yields. At this stage, the bending stiffness of the joint decreases, even by an order of magnitude (Li Xin-Xing and Cao 2015). Figure 26 shows a two-stage method for determining the bending stiffness of a transverse joint. The two phases are the stable phase OA and the nonsteady phase AB. The slopes K1 and K2 corresponding to the OA segment and AB segment are the joint bending stiffness values of the stable phase and unstable phase. The difference between K1 and K2 is larger. When the bending stiffness of joint is K1, the joint is in the normal stable working state; when the bending stiffness of joint is K2, the joint section is in a nonsteady state, usually with cracks.

Figure 26 shows that under the condition of different axial force and bending moment combination conditions, when the joint section is subjected to a stable force, the bending stiffness of joint does not change, and it becomes its own attribute of the joint and has nothing to do with the external load. In the calculation of an actual pipe corridor design, the bending stiffness of the joint can be selected by using the method of two-stage bending stiffness of transverse joint proposed in this paper.

7. Conclusions
In this study, a mechanical model which can characterize the various stages of transverse joint from force to failure and the corresponding theoretical analytical expressions were established. Then, a sensitivity analysis of the factors affecting the bending stiffness of the joint was carried out by numerical simulation. Finally, the theoretical calculation results and the numerical simulation results were compared to obtain the variation trend of bending stiffness of transverse joints. A method is proposed for determining the bending stiffness of transverse joints.

(1) According to the change process of transverse joint section, a calculation model and analytical formula are proposed for the bending stiffness of transverse joint. A comparison between the calculation results and simulation results shows that they agree well.

(2) When the bending moment of transverse joint section is small, the bending moment-corner curve increases linearly. As the bending moment increases, the concrete crushes, and the bolt yields. The curve grows slowly. When the influencing depth of concrete compressive strain in the compression zone is 0.5 H, the theoretical calculation result and numerical simulation result are closer. Therefore, it is recommended to take 0.5 H as the influencing depth of concrete compressive strain in the compression zone in the theoretical calculation model of transverse joint bending stiffness.

(3) The performance of transverse joint bending stiffness is less affected by the bolt tightening force, increasing the tightening force of the bolt; the joint section angle is reduced slightly; the joint bending stiffness is increased. The radial position of the bolt affects the stability of compression section of joint section. When the axial force increases, the effect of bolt position on the bending stiffness of joint is reduced. The thickness of transverse joint significantly affects the joint stiffness. The thicker the joint, the greater the height of joint section of joint, and the constraint on the joint section is correspondingly increased, that is the space and capacity of joint section are reduced correspondingly, resulting in an increase in the bending stiffness.

(4) According to the variation trend of bending stiffness curve of transverse joint, the bending stiffness
of transverse joint can be divided into the unsteady stage stiffness and stable stage stiffness, and the two-stage bending stiffness value method is proposed for the transverse joint of utility tunnel joint.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Funding**

This work was conducted with supports from the National Natural Science Foundation of China (Grant Nos. U1602232 and 51474050), the Fundamental Research Funds for the Central University (N170108029); Doctoral Scientific Research Foundation OF Liaoning Province (Grant No. 20170540304; 20170520341). The research and development project of China construction stock technology (CSCEC-2016-Z-20-8).

**References**

Canto-Perello, J., and J. Curiel-Esparza. 2013. “Assessing Governance Issues of Urban Utility Tunnels.” *Tunneling and Underground Space Technology* 33 (7): 82–87. doi:10.1016/j.tust.2012.08.007.

Chen, Y., P. Sareh, J. Feng, Q. Sun, et al. 2017. “A Computational Method for Automated Detection of Engineering Structures with Cyclic Symmetries.” *Computers & Structures* 191: 153–164. doi:10.1016/j.compstruc.2017.06.013.

Chen, Y., Q. Zhang, J. Feng, Z. Zhang, et al. 2019. “Experimental Study on Shear Resistance of Precast RC Shear Walls with Novel Bundled Connections.” *Journal of Earthquake and Tsunami* (109). doi:10.1142/S1793431194000025.

Chen-Jun, J. L. Z., J. Li, and X. J. Shi. 2012. “Numerical Simulation of Shaking Table Test on Utility Tunnel under Non-uniform Earthquake Excitation.” *Tunneling and Underground Space Technology* 30 (4): 205–216. doi:10.1016/j.tust.2012.02.023.

Choi H.K, Y C Choi, and C.S. Choi (2013). “Development and Testing of Precast Concrete Beam-to-Column Connections.” *Engineering Structures* 56: 1820–1835.

Feng Kun, H.C., and X. Ming-qing. 2016. “Flexural Test of Joints of Segmental Joints of Shield Tunnel under High Axial Pressure.” *China Civil Engineering Journal* 8 (6): 99–110.

Hunt, D. V. L., D. Nash, and C. D. F. Rogers. 2014. “Sustainable Utility Placement via Multi-Utility Tunnels.” *Tunneling and Underground Space Technology* 39 (8): 15–26. doi:10.1016/j.tust.2012.02.001.

Jiang Hong-sheng, H. X.-Y. 2004. “Theoretical Study of Rotating Stiffness of Joint in the Shield Tunnel Segments.” *Chinese Journal of Rock Mechanics and Engineering* 23 (12): 1574–1577.

Jiang Jian-jing, L. X.-Z., and Y. Lie-ping. 2005. “Finite Element Analysis of Concrete Structures.” *Journal of Tsinghua University (Science and Technology)* 32 (1): 47–48.

Julian Canto, P., J. Curiel-Esparza, and V. Calvo. 2013. “Criticality and Threat Analysis on Utility Tunnels for Planning Security Policies of Utilities in Urban Underground Space.” *Expert Systems with Applications* 40 (5): 4707–4714. doi:10.1016/j.eswa.2013.02.031.

Llobb, L., O. Blanpain, and F. Buyle-Bodin. 2004. “Promoting the Urban Utilities Tunnel Technique Using a Decision-making Approach.” *Tunneling and Underground Space Technology* 12 (3): 256–261.

Li Xin-Xing, Y. Z.-H., and W.-H. Cao. 2015. “Model Test Study on Joint Stiffness of Super-tunnel Assembled Segment Joints.” *China Civil Engineering Journal* 23 (52): 315–320.

Li Yu-Jie, H. P. 2012. “Influence Analysis on Longitudinal Dislocation for Shield Tunnel Segment.” *Engineering Mechanics* 29 (8): 277–282.

Perello, J. C., and J. Curiel-Esparza. 2007. “An Analysis of Utility Tunnel Viability in Urban Areas.” *Civil Engineering and Environmental Systems* 25 (2): 11–17. doi:10.1080/10286600600562129.

Sun Wen-Hao, J. Q.-Z., and Y. Lan. 2008. “Research on the Factors Influencing Flexural Rigidity of Duct Piece Joint of Shield Tunnel.” *Journal of Railway Engineering Society* 38 (1): 66–71.

Todut, C., D. Dan, and V. Stoian. 2014. “Theoretical and Experimental Study on Precast Reinforced Concrete Wall Panels Subjected to Shear Force.” *Engineering Structures* 80: 323–338. doi:10.1016/j.engstruct.2014.09.019.

WANG Peng-yu, W. S.-H., A. Li, and P. J. Jie Ru La. 2018. “Numerical Experiment and Calculation of Mechanical Behavior of Utility Tunnel Joint.” *Journal of Northeastern University* 39 (12): 1788–1793.

Wang Shu-Hong, A. L. P. J. J. R. L., and W. Peng-yu. 2018. “Mechanics Performance Analysis of Precast Rectangle Box Culvert in Different Burial Depth and Damage Prediction of Key Parts.” *Journal of Northeastern University* 39 (2): 260–265.

Wei-Chen, X. 2002. “Progress of Studies and Applications of Precast Concrete Frame Structure Systems.” *Industrial Construction* 32 (1): 47–50.

Xue Wei-Chen, W. H.-D. 2009. “Special Structures Experimental Studies on Waterproof Performance Test Research of PPMT in Shanghai Expo Area.” *Special Structures* 26 (1): 109–113.

Yoo, C., and J. H. Kim. 2003. “A Web-based Tunneling-induced Building/utility Damage Assessment System: TURKISH.” *Tunneling and Underground Space Technology* 18 (2): 497–511. doi:10.1016/S0886-7798(03)00067-1.

Zhang Jian-Gang, H. C. 2013. “Model of Mechanical Behavior with Whole Segmental Lining of Shield Tunnel.” *Engineering Mechanics* 30 (1): 136–141.

Zhang, L. F., and K. Fang Ruo-Quan. 2017. “Experiment on Flexural Performance of Shield Tunneling Prototype Segment Joints.” *China Civil Engineering Journal* 23 (S2): 220–230.