

# Seismic analysis on cross joint of utility tunnel

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**Abstract.** The finite element software ABAQUS is used to establish the seismic time-history analysis model of the utility tunnel joints. The viscoelastic boundary is employed to input the seismic wave through the equivalent nodal force. Considering the nonlinearity of the soil and concrete materials, the internal force of the cross-shaped utility tunnel is calculated, and the influence effect and influence range of the cross joints of the utility tunnel are also studied. Studies have shown that the internal forces near the cross joints increase significantly. The research has certain reference value for the seismic design of the cross joints in utility tunnel.

## 1 Introduction

Over the years, with the rapid development of utility tunnel construction, the seismic performance of the cross joints of utility tunnel has received extensive attention. Earthquakes occur frequently in China, the seismic analysis of utility tunnels and their cross-joints is of great significance for the seismic design of utility tunnel. Takada [1] studied the seismic design principles and methods of underground pipelines, and proposed initial practical parameters and formulas, and compared the seismic design of the lifeline in terms of earthquake ground motion input, stratum and pipeline deformation from the perspective of application. Yue [2] and Yue et al [3] used the comparative experiment and three-dimensional finite element model to achieve the research and analysis on the utility tunnel, and considered many factors affecting the structural response in the analysis, such as the influence of artificial boundary conditions, contact surfaces and soil plasticity. Through theoretical derivation, different ground motion input methods of underground structure are discussed and the displacement input is recommended as a more accurate input method. Liu et al. [4] studied the error source of the quasi-static method of underground structures through finite element software comparison analysis, and improved and optimized the seismic wave loading method of the reaction acceleration method. Shi et al. [5] established a three-dimensional dynamic finite element numerical model for a dual-compartment utility tunnel and applied a pulse load to the boundary of the model to generate Rayleigh waves, and compared that with the conventional time-history analysis considering only the bottom lateral action, Through this comparison, the effects of different soil constitutive models, buried depths, incident angles and different cross-sections on the seismic behavior of the utility tunnel under the combined action of Rayleigh wave and

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bottom seismic acceleration are studied. However, there are relatively few related researches on complex cross-joints of utility tunnel. In this paper, the finite element software ABAQUS is used to establish a nonlinear time-history analysis model for the cross joints in utility tunnels. Considering the nonlinearity of the soil and concrete materials, the dynamic analysis on joints in utility tunnel is carried out by using the viscoelastic boundary and the method of inputting seismic waves by equivalent nodal force. Based on that, the influence effect and influence range of the cross joints of utility tunnels are studied. This study has certain reference value for the seismic resistance of the cross joints of utility tunnels.

## **2 CALCULATION METHOD**

### **2.1 Viscoelastic artificial boundary**

In this paper, the nonlinear time-history analysis method is used and a three-dimensional soil-pipeline model using the finite element software ABAQUS is established. By applying a viscoelastic boundary and equivalent nodal force [6] at the boundary of the soil layer, equivalent linearization analysis [7] of soils is performed.

### **2.2 Seismic input of viscoelastic artificial boundary**

The seismic wave acting at the viscoelastic artificial boundary consists of two parts, one part is the original incident seismic wave, and the other part is the reflected wave generated by the internal seismic wave at the boundary position, and the equivalent node force applied is to simulate the effects of these two waves, thus to ensure that the displacement and stress at the artificial boundary are consistent with the original free field. In this paper, the response of the free field is first obtained according to the EERA program [8], and then converted into the equivalent nodal force applied at the viscoelastic boundary node to perform the input of the seismic wave.

### **2.3 Damage plasticity model for concrete in ABAQUS**

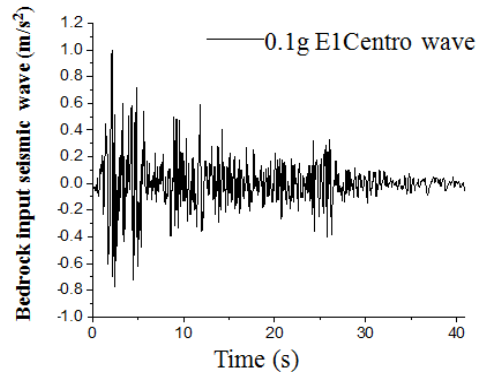
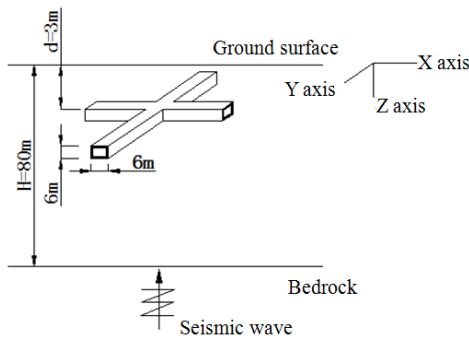
The concrete damage is based on the concrete damage plasticity CDP model [9-10] in ABAQUS software. The CDP model in ABAQUS combines isotropic tensile plasticity theory, isotropic compression plasticity theory and isotropic damage theory to describe the inelastic behavior of concrete. It is a continuum model considering plasticity and damage [11], which is mainly used to describe unidirectional loading, repeated loading and dynamic loading. In use, it is necessary to input the corresponding relationship between yield stress and inelastic strain, damage factor as well as stiffness recovery factor in ABAQUS. ABAQUS automatically converts inelastic strain into equivalent plasticity strain when performing analysis, and determines the elastic modulus of concrete according to the stiffness recovery factor and the damage factor. Relevant parameters are determined according to the relevant specification [12].

## **3 NONLINEAR SEISMIC RESPONSE ANALYSIS OF CROSS-JOINT UTILITY TUNNEL**

### **3.1 Calculation parameters of utility tunnel cross-joint model**

The one-way utility tunnel in the X-axial direction is named as a one-way X-direction utility tunnel; the one-way utility tunnel in the Y-axial direction is named as a one-way Y-direction utility tunnel; as shown in Fig. 1, in cross-shaped utility tunnel, the utility tunnel in X direction is named as the cross X-direction utility tunnel, and that in the other direction is named as the cross Y-direction utility tunnel.

Parameters of the horizontal layered site are shown in Table 1. The utility tunnel has a buried depth of 3 m, a cross section of 6 m×6 m and a thickness of 0.3 m. The concrete material parameters are shown in Table 2. The seismic wave uses an El Centro wave with a peak value of 0.1 g, which is incident perpendicularly from the bedrock surface and vibrates along the X axis. The acceleration time history curve is shown in Fig. 2. The equivalent linear parameters of soil materials are shown in Fig. 3.



**Fig. 1.** Cross-joint utility tunnel problem model.

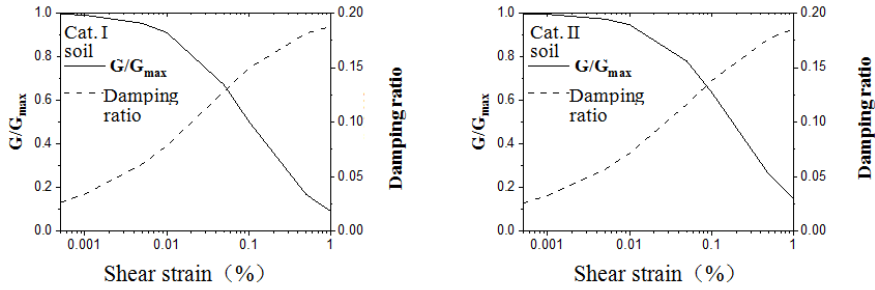
**Fig. 2.** 0.1 g El Centro wave.

**Table 1.** Soil layer material parameters.

Soil layer number	Category	Thickness (m)	Shear wave velocity(m/s)	Density (kg/m3)	Damping ratio
1 (Ground surface)	I	10	150	1750	0.05
2	I	10	175	1775	0.05
3	I	10	200	1800	0.05
4	I	10	250	1850	0.05
5	II	10	300	1900	0.05
6	II	10	350	1950	0.05
7	II	10	400	2000	0.05
8	II	10	450	2050	0.05
9 (Bedrock)		∞	500	2100	0.02

**Table 2.** Concrete material parameters

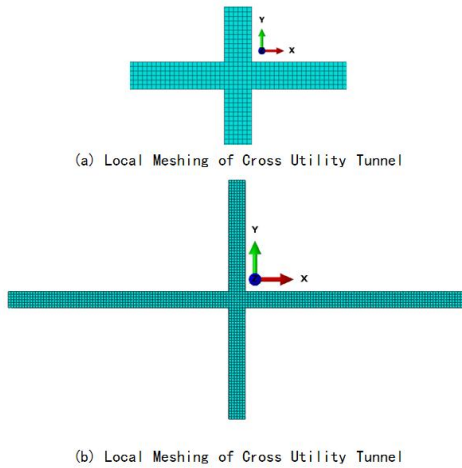
Concrete	Density (kg/m3)	Elastic Modulus (MPa)	Damping Ratio
C60	2600	35500	0.05



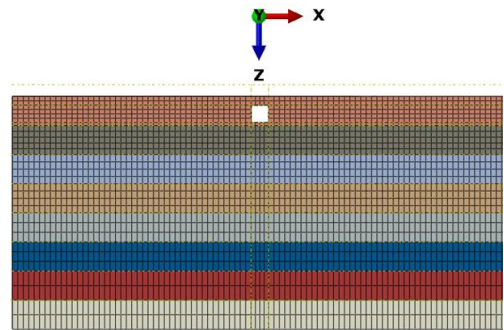
**Fig. 3.** Soil nonlinear characteristic curve.

### 3.2 Model establishment

According to the above analysis, the size of the model is 170 m×90 m×80 m (X×Y×Z), the one-way X-direction utility tunnel is 170 m long and the one-way Y-direction utility tunnel is 90 m long, and the cross X-direction utility tunnel and cross Y-direction utility tunnel are respectively 170 m and 90 m long. The utility tunnel uses the S8R shell unit. The utility tunnel meshing is shown in Fig. 4, and the soil meshing is shown in Fig. 5.



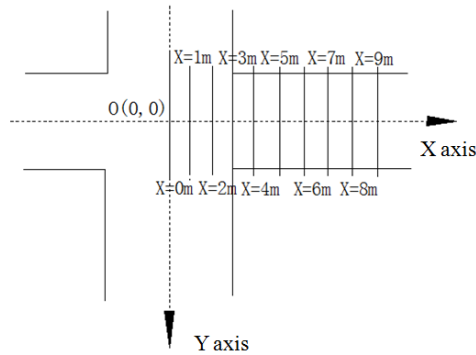
**Fig. 4.** Utility tunnel meshing.



**Fig. 5.** Meshing.

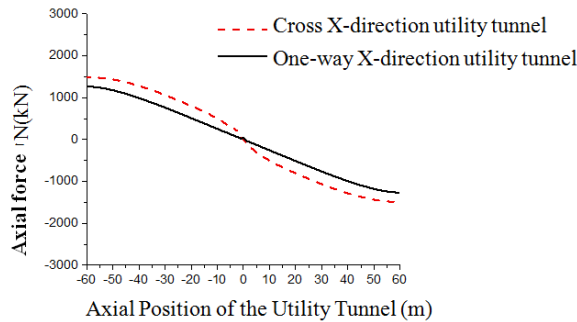
### 3.3 Internal force analysis of X-direction utility tunnel at the cross joint of utility tunnel

The axial force  $N$ , the shear force  $V$  and the bending moment  $M$  of the cross one-way X-direction utility tunnel when maximum seismic motion emerges in X-direction are compared with the internal force of the one-way X-direction utility tunnel to explore the influence range and influence effect of the utility tunnel cross-joint on the cross X-direction utility tunnel. Analytical section positions of cross X-direction utility tunnel are as shown in Fig. 6.



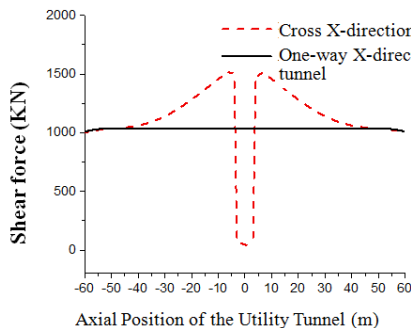
**Fig.6.** Schematic analytical section of cross X-direction utility tunnel.

As shown in Fig. 7, the existence of the cross-joint increases the axial force  $N$  of the cross X-direction utility tunnel. At the cross joint ( $X=3$  m), the increment of axial force  $N$  reaches the maximum increased by about 280%; When the distance from the cross joint increases, the influence to the axial force is weakened. At a distance of 35 m from the axial center section of the utility tunnel, the axial force  $N$  increases by about 30%, and at 60 m, it increases by 16%.



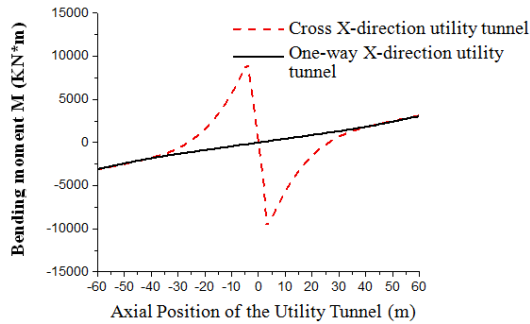
**Fig. 7.** Axial force comparison of X-direction utility tunnel

As presented in Fig. 8, the shear force  $V$  of the cross X-direction utility tunnel in the joint area declines greatly, close to 0; at the cross-joint position ( $X=3$  m), the shear force  $V$  increases sharply, which is 1500 kN, increased by about 50% relative to the one-way X-direction utility tunnel; then the shear force  $V$  is gradually reduced, and the difference between it and that of the one-way X-direction utility tunnel is within 5% at a distance of 35 m from the axial center section of the utility tunnel.



**Fig. 8.** Shear force  $V$  Comparison of X-direction utility tunnel.

As given in Fig. 9, with respect to the axial force  $N$  and the shear force  $V$ , the existence of the cross joint makes the increase effect of the bending moment  $M$  of the cross X-direction utility tunnel most obvious, and becomes the control internal force of the section; at the cross-joint position ( $X=3$  m), the bending moment  $M$  is 9700 kN·m, and then the increasing effect of the joint is rapidly reduced. At a distance of 35 m from the axial center section of the utility tunnel, the difference between the bending moment  $M$  and that of the one-way X-direction utility tunnel is within 5%.



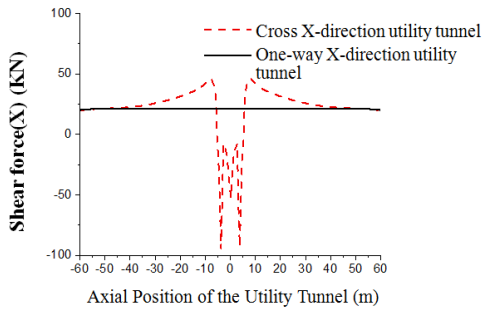
**Fig. 9.** Bending moment  $M$  comparison of X-direction utility tunnel.

In summary, the influence range of the cross joint is  $35 \times 2 = 70$  m. The cross joint increases the axial force  $N$  and the bending moment  $M$  of cross X-direction utility tunnel, and decreases the shear force  $V$  inside the cross-joint area while increases that outside the area. And the internal force increase effect is most obvious at the cross-joint position.

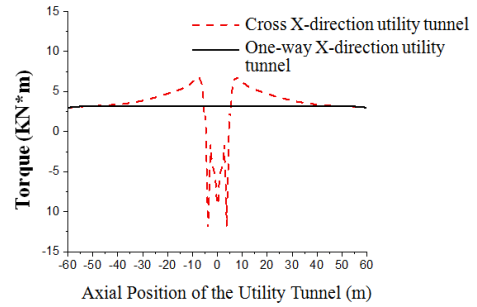
Fig. 10 shows that the shear force  $FV(X)$  of the cross X-direction utility tunnel increases inversely, which is -52.6 kN at the center position ( $X=0$ m), and increases by about 150% in the reverse direction; The increase effect at the cross-joint position ( $X=3$ m) is most pronounced, with a shear force  $FV(X)$  of -93 kN i.e. a reverse increase by approximately 350%. At a distance of 7m from the axial center section of utility tunnel, the maximum positive increase emerges, that is 45.8 kN; then the increase effect is gradually weakened, the analysis unit shear force  $FV(X)$  difference between the cross X-direction utility tunnel and one-way X-direction utility tunnel is within 5% at a distance of 40 m from the axial center section of the utility tunnel.

It is presented in Fig. 11 that the torque  $FT$  change of the cross X-direction utility tunnel is similar to the shear force  $FV(X)$ , and the torque  $FT$  in the cross-joint area increases inversely, and is -9.1 kN at the center position ( $X=0$  m), a reverse increase of about 180%; the increase effect at the cross-joint position ( $X=3$  m) is most obvious, with a torque  $FT$  of -11.8 kN·m and a reverse increase of about 260%. At a distance of 7m from the axial center section of utility tunnel, the maximum positive increase emerges, that is 6.82 kN·m; then the increase effect is gradually weakened, the analysis unit Torque  $FT$  difference between the cross X-direction utility tunnel and the one-way X-direction utility tunnel is within 5% at a distance of 40 m from the axial center section of the utility tunnel.

To conclude, the cross joint exerts influence on the shear force  $FV(X)$  and torque  $FT$  in a larger area, which is  $40 \times 2 = 80$ m. The cross joint increases the shear force  $FV(X)$  and the torque  $FT$  of the analysis unit, wherein reverse increase appears in the cross-joint area and the increase effect at the cross-joint position is the largest.



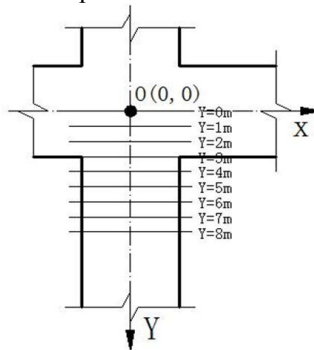
**Fig. 10.** Analysis unit shear force FV (X) comparison of X-direction utility tunnel.



**Fig. 11.** Analysis unit torque FT comparison of X-direction utility tunnel.

### 3.4 Internal force analysis of Cross Y-direction utility tunnel

Fig. 12 shows the analysis section position of the cross Y-direction utility tunnel.



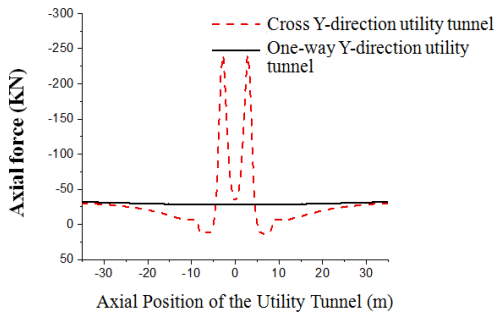
**Fig. 12.** Schematic analytical section of cross Y-direction utility tunnel.

As shown in Fig. 13, the existence of the cross joint increases the axial force FN in the cross-joint area. At the cross-joint position (Y=3m) and the axial force FN is the largest, which is -240.6 kN, increased by about 750% compared with the one-way Y-direction utility tunnel; The axial force FN outside the cross-joint area is smaller than that of the one-way Y-direction utility. With the distance from the cross joint increases, the cross-joint effect on the axial force FN decreases gradually. At Y=35 m, the axial force difference of analysis unit at the corresponding position of cross Y-direction utility tunnel and one-way Y-direction utility tunnel is within 5%.

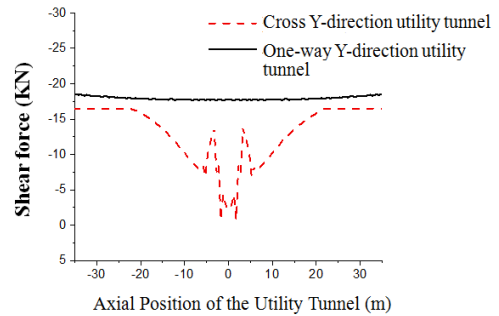
As presented in Fig. 14, the existence of the cross joint makes the shear forces FV of the cross Y-direction utility tunnel smaller than the one-way Y-direction utility tunnel, but the shear force FV at the cross-joint position (Y=3 m) is larger than those at other positions of the analysis unit in the cross-joint area due to stress concentration. At Y=35 m, the analysis unit shear force difference between the cross Y-direction utility tunnel and the one-way utility tunnel is within 10%.

Fig. 15 shows that the influence of the cross joint on the bending moment FM of the analysis unit is similar to that on the axial force FN. The maximum bending moment FM is also found at Y=3 m, which is -41.2 kN·m, increased by about 136 % relative to the one-way Y-direction utility tunnel; except locations near the cross-joint position, the bending moments FM at other locations are smaller than those of the one-way Y-direction utility

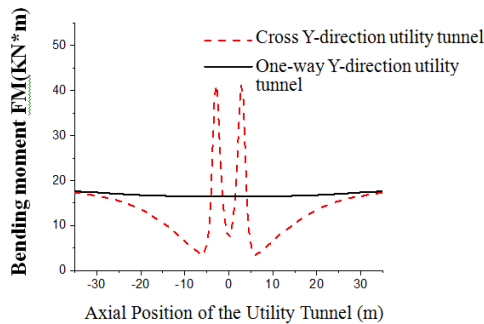
tunnel. At  $Y=30$  m, the bending moment difference with the one-way Y-direction utility tunnel is within 5%.



**Fig. 13.** Analysis Unit Axial Force FN Comparison of Y-direction Utility Tunnel



**Fig. 14.** Analysis Unit Shear Force FV Comparison of Y-direction Utility Tunnel



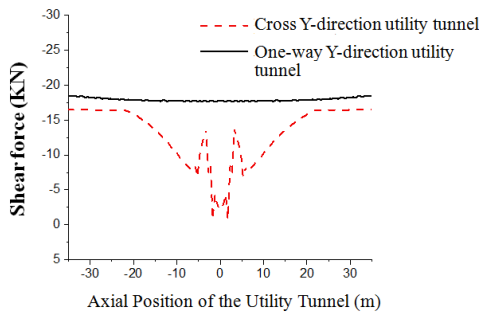
**Fig. 15.** Analysis Unit Bending Moment FM Comparison of Y-direction Utility Tunnel

To sum up, the existence of the cross joint reduces the axial force FN, the shear force FV and the bending moment FM of the cross Y-direction utility tunnel except locations near the cross-joint position. This is because a larger stiffness at the cross-joint position makes the shear deformation smaller than the one-way Y-direction utility tunnel, thus leads to the decrease of the axial force FN, shear force FV, and bending moment FM outside the cross-joint area, while an increase of the axial force FN, shear force FV, and bending moment FM appears due to stress concentration at the cross-joint position. The influence range of the cross joint on the shear force FV is larger than that on the bending moment FM and the axial force FN, but compared with the influence effect of the shear force FV at the cross-joint position ( $Y=3$  m), the influence effect of 10% shear force difference at  $Y=35$  m can be neglected. It can be considered that the influence range of the cross joint on the cross Y-direction utility tunnel is  $35 \times 2 = 70$  m.

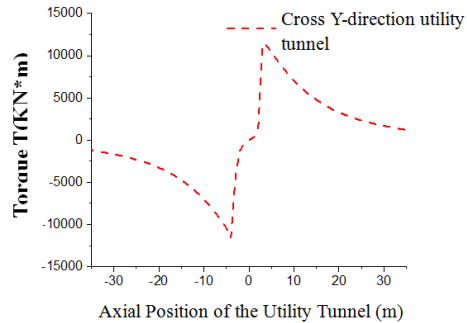
As shown in Fig. 16 and Fig. 17, in addition to the influence on the axial force FN, the shear force FV and the bending moment FM on the cross section of the cross Y-direction utility tunnel, the existence of cross joint also generates section shear force  $V$  and the torque  $T$ . For the shear force  $V$ , the maximum value appears at the cross-joint position ( $Y=3$  m), which is 194.7 kN, and then it decreases gradually. For the torque  $T$ , the maximum value also appears at  $Y=3$  m, which is 11360 kN·m, and it decreases with the increase of the distance from the cross joint. In the range of  $Y=20$  m, both shear force  $V$  and torque  $T$  decline more steeply, which is the main influence area of the cross joint; in contrast to the shear force  $V$  and the torque  $T$  at the cross-joint position, the shear force  $V$  and torque  $T$  generated at  $Y=35$  m is negligible. The torque  $T$  generated by the cross joint becomes the control internal force of the section, and its increase effect is far greater than the reduction

effect of the cross joint on the axial force FN, the shear force FV and the bending moment FM of the cross section, so the cross joint also has an adverse effect on the cross Y-direction utility tunnel.

The calculation shows that the axial force FN in the cross section of the cross Y-direction utility tunnel increases in the cross-joint area (between Y=-3 m and Y= 3 m), and the maximum value of 466.1 kN emerges at the cross joint (Y=3 m); axial force FN outside the cross-joint area is smaller than that of the one-way Y-direction utility tunnel, and with the increase of the distance from the cross joint, the reduction effect of the cross joint on the axial force FN is gradually weakened; the maximum axial force FN of each analysis section appears near the lower corner.



**Fig. 16.** Shear force  $V$  distribution of Cross Y-direction utility tunnel



**Fig. 17.** Torque  $T$  distribution of Cross Y-direction utility tunnel

## 4 Conclusions

The research shows that the cross joint increases the internal force of the utility tunnel which vibrates in the axial direction of the utility tunnel, and the bending moment  $M$  becomes the control internal force of the section. The increase effect on internal force is the most obvious at the cross-joint position. The presence of the cross joint causes the shear force  $V$  and the torque, wherein the torque becomes the control internal force of the section in another utility tunnel.

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