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Design Model and Inversion Analysis of Shield Lining Segments

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Abstract: The design of shield lining segments is mostly calculated by load-structure method. The rationality of structural calculation mainly depends on the structural model and the accuracy of the applied loads. At present, the models used in shield tunnel segment design mainly include: beam-spring model and beam-joint model. The beam-joint model is more accurate, but the simulation is mostly realized by self-programming. In this paper, the numerical simulation is carried out by the general finite element software ANSYS. The two types of models are compared and analyzed, and the action load is analyzed by the beam-joint deformation discontinuity model.

Key words: shield lining segment; design model; inversion analysis; ANSYS

0. Foreword

The lining structure of the shield tunnel is usually composed of the tube piece, the connecting bolt between the tube sheets and the waterproof filling material, as shown in Fig. 1. At present, the shield tunnel segment design is mostly calculated by the load-structure method. The main models are beam-spring and beam-joint. [1] The beam-joint model can better describe the mechanical properties between the segments, and the joint can be simulated by setting a spring. According to the mechanical characteristics of the joint, the beam-joint model is further divided into: beam-joint deformation continuous model and beam-joint deformation discontinuous model. The joint deformation discontinuity means that the stress-strain relationship of the joint is nonlinear. [1,2,3]

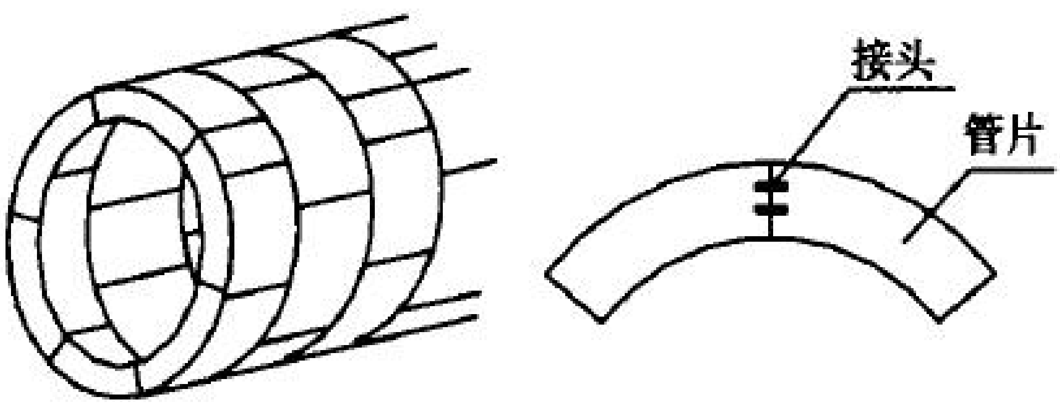

Figure 1. Shield tunnel lining structure and segments

接头：Connector

管片：Segment

When using the load-structure method, in addition to the reasonable structural model, the reasonable design of the shield tunnel is inseparable from the reasonable soil pressure load distribution pattern and the distribution pattern of the reaction force generated by the compression deformation of the soil response structure. However, the calculation and research of earth pressure mostly emphasizes the experience summary, and in the actual measurement of earth pressure of shield pipe, it is limited to the current soil pressure monitoring level and construction influence, so the measured value of earth pressure is not reliable [4]. With the rapid development of domestic subway construction, the depth of tunnels, the increase of shield sections and the occurrence of construction cases in complex special strata, it is not certain whether the existing method of determining the design load of the segment can ensure the safety of the segments or not. Therefore, the development of the tube earth pressure calculation method in line with the actual shield engineering is an important research topic in the design of the tube sheet. [1,4,11]

In response to the above topics, the back analysis method provides a better solution. This type of method is based on the displacement and stress values obtained from on-site measurements. These data can be used not only for the basic data of information design and construction, but also for the inversion analysis of the applied loads of the structure. Domestically, Zhu Hehua (1996) of Tongji University and Zhu Wei and Zhong Xiaochun (2004) of Hohai University have done a lot of meaningful research in this respect[1,3,4]. Based on the measured data of the internal force of the segment (such as axial force and bending moment) which are relatively easy to measure, they use the optimization method based on the discontinuity model of beam-joint deformation to analyze the magnitude and distribution of the earth pressure acting on the segment, and serve the actual engineering design. However, the beam-joint deformation discontinuity model and the optimization process are mostly implemented by self-programming calculation programs, such as Zhu Hehua's non-derivative search simplex method (Tongji independently developed shuguang positive and negative analysis software) and Zhong Xiaochun's complex shape method, which relatively improved the technical threshold for the application of inversion analysis technology in shield tunnel engineering.[3,4,7]

1. Design Model of Shield Lining Segments

At present, the shield tunnel segment design is mostly calculated by the load-structure method. The main models are beam-spring and beam-joint. The commonly used elements in the design are formation spring unit, beam unit and joint unit. The two types of models can be divided into various categories according to the formation reaction force, beam unit calculation and joint effect.

1.1 Formation spring

Both beam-spring and beam-joint models use springs to account for the reaction of the formation. Such springs can be called formation springs. About the formation spring: The reaction force of the lining structure includes the tangential reaction force (friction) and the radial reaction force, so the setting of the formation spring can be further divided into the formation radial spring and the formation tangential spring;formation spring In response to structural deformation, tension or pressure may be generated, so the formation spring may be further divided into a formation tension spring and a formation compression spring. Since the formation is basically not subjected to tensile forces, we need to remove the tension formation springs. The model at this time is called the local formation spring model.

1.2 Beam unit

Both beam-spring and beam-joint models use beam elements to simulate lining segments. The beam element is further divided into a straight beam unit and a curved beam unit, and the calculation of the curved beam unit is more accurate.

Although the segment is curved, in the calculation and analysis process, if the length of the element is made small enough, the straight beam element is used instead of the curved beam element, and the calculation results of the two are very close [6]. Therefore, the straight beam unit is used for the simulation of the lining segments.

1.3 Connector unit

The beam-joint model takes into account the joint effect of the segments. The mechanical properties of the joint simulate the axial, shearing and rotational effects by providing three springs at the joint. Such springs can be referred to as joint springs. The deformation of the joint part of the assembled lining structure is discontinuous. According to whether the beam-joint model describes the nonlinear shape of the joint, the beam-joint model can be divided into: beam-joint deformation continuous model and beam-joint deformation discontinuity model.

2. Calculation Comparison of Design Models

2.1 Design model

The author uses the general finite element software ANSYS to write a program to compare and analyze the two types of models. The model is shown in Figure 2 - Figure 4. The model points are shown in Table 1. The model Model-1 and the model Model-2 belong to the beam-spring model. Model Model-3 belongs to the beam-joint model (constant nonlinear of joint deformation can be considered).

Table 1. Calculation model

Design model	Model category	Calculation points	Selection unit
Model-1	Beam-spring model	Formationspring (Radial, local)	Linear linear beam unit、Linear spring unit
Model-2	Beam-spring model(including tangential spring)	Formation spring(radial, tangential, local)	Linear linear beam unit、Linear spring unit
Model-3	Beam-spring model(deformation is not continuous)	Joint spring、Formation spring (radial, tangential, local)	Linear linear beam unit、Linear spring unit、Nonlinear spring unit

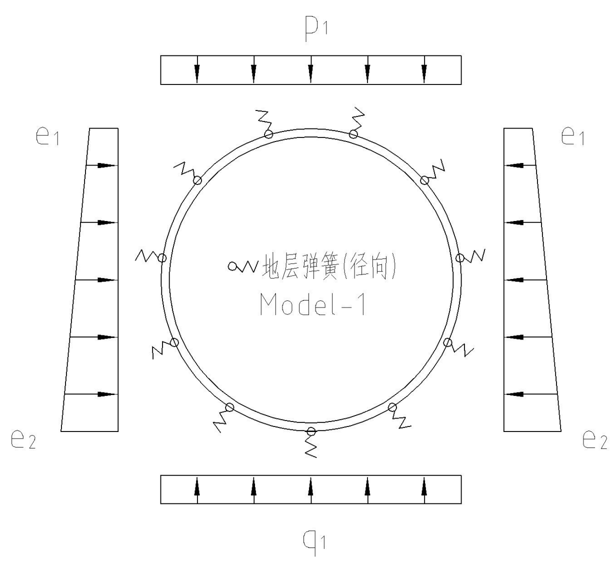

Figure 2. Design Model: Model-1

地层弹簧（径向）：Formation spring (radial)

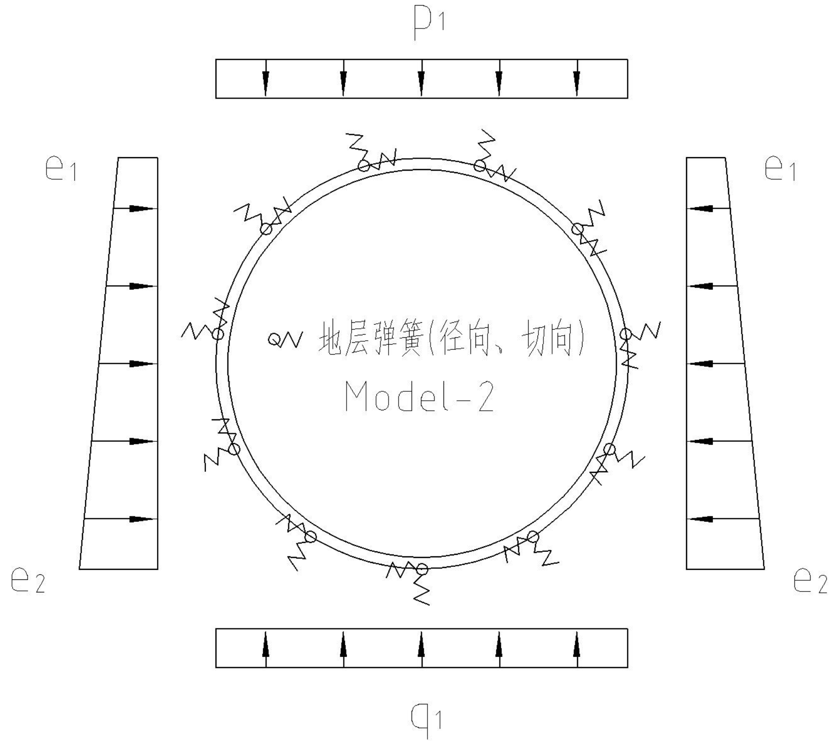

Figure 3. Design Model: Model-2

地层弹簧（径向 切向）：Formation spring (radial，tangential)

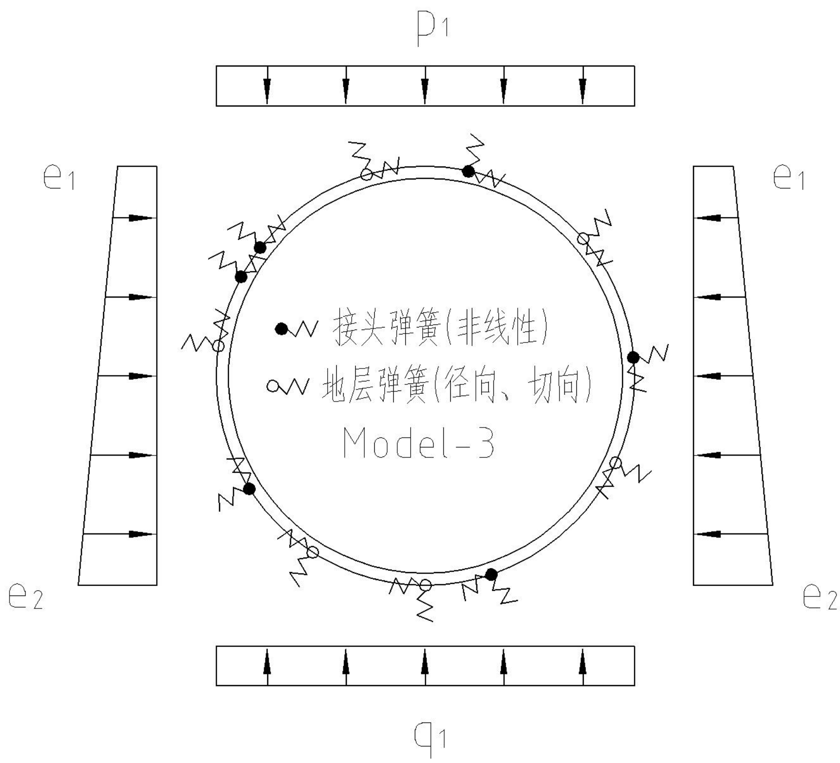

Figure 4. Design Model: Model-3

接头弹簧（非线性）：Joint spring (non-linear)

地层弹簧（径向 切向）：Formation spring (radial，tangential)

2.2 Calculation example

In this example, the section A of section B of a subway line 7 project is used as the calculation section. The section A shield tunnel is located in the sandy soil layer, the center of the tunnel is 19m away from the surface, and the groundwater level is buried 3m. The ϕ 5.44m earth pressure balance shield machine was used for tunnel construction, and synchronous grouting technology was adopted. The lining ring consists of 3 standard segments, 2 adjacent segments, and 1 closed tube. The joint position is shown in Figure 5. The reinforced concrete lining pipe has a width of 1.2m, a thickness of 280mm and an outer diameter of 5.3m. The elastic modulus of the segment concrete is $E = 3.5 \times 10^7$ Kpa, and the reaction coefficient of the foundation is $K = 20$ Mpa/m. Earth pressure load component, $p_1 = 203$ kN/m2, $q_1 = 210$ kN/m2, $e_1 = 161$ kN/m2, k $e_2 = 224$ N/m2. The segment joints in the design model Model-3 were selected according to experience: axial stiffness $K_n = 2.5 \times 10^8$ kN/m, shear stiffness $K_s = 6.55 \times 10^7$ kN/m, rotational stiffness $K_\theta^+ = 1.5 \times 10^6$ kN•m/rad (outer tension), $K_\theta^- = 2.5 \times 10^6$ kN•m/rad (inside pulled). (Note: The rotational stiffness here simply uses a double straight line to express the difference between the inner and outer tensile stiffness. When the structural mechanical parameters in the beam-joint model are strictly required, it can be obtained by the tube joint bending and shear test. Bending test data, the nonlinear spring unit can better simulate the nonlinear relationship between stress and strain at the joint).

The calculated bending moments of each model under the same calculation conditions are shown in Fig. 6-8, and the safety factor results according to the section strength of the damage stage are shown in Fig. 9-11.

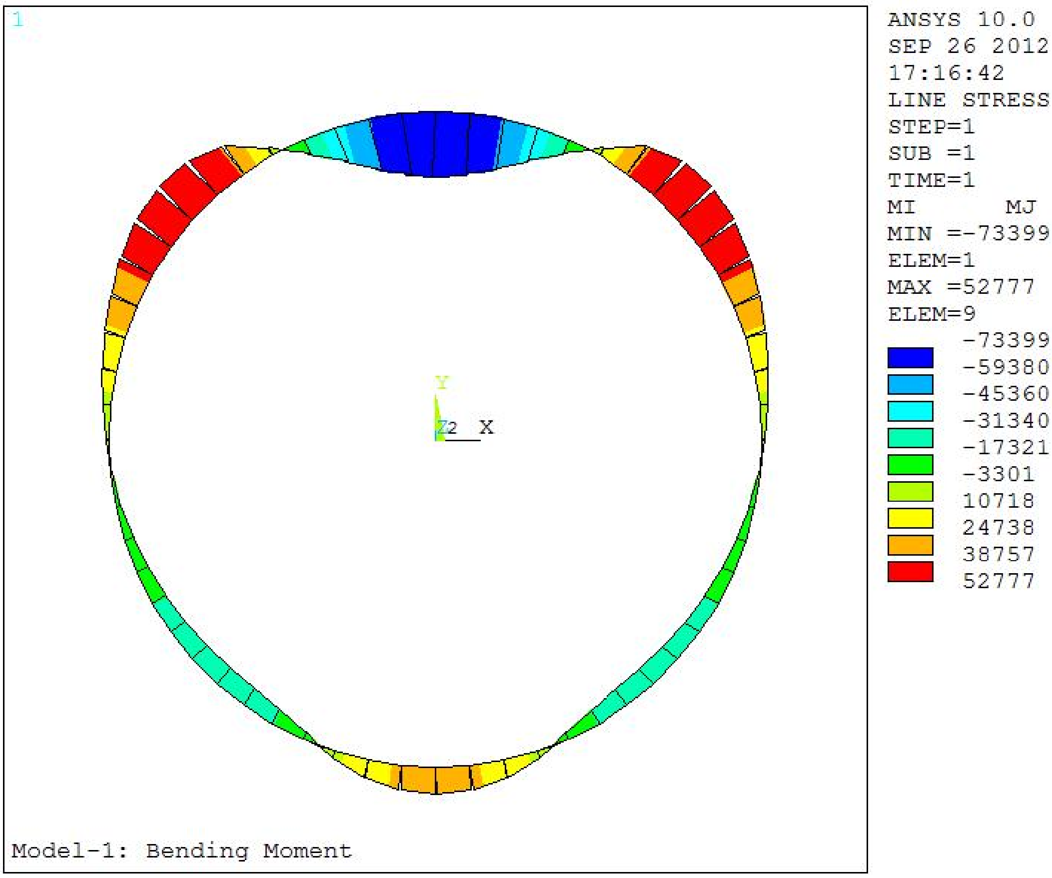

Figure 5. Design Model Model-1: Moment Diagram

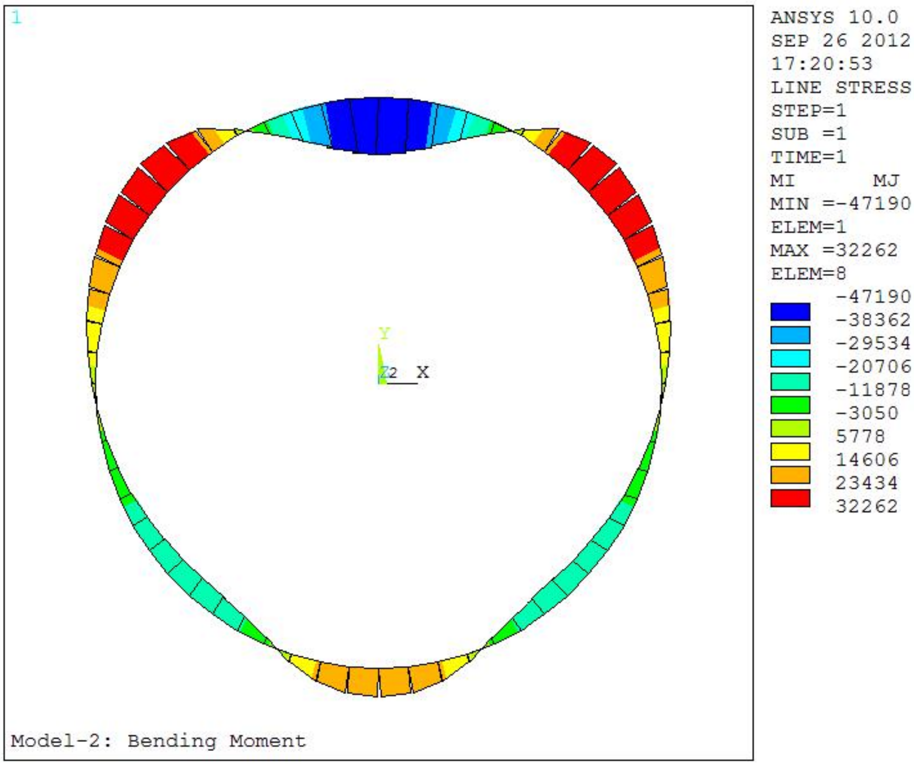

Figure 6. Design Model Model-2: Moment Diagram

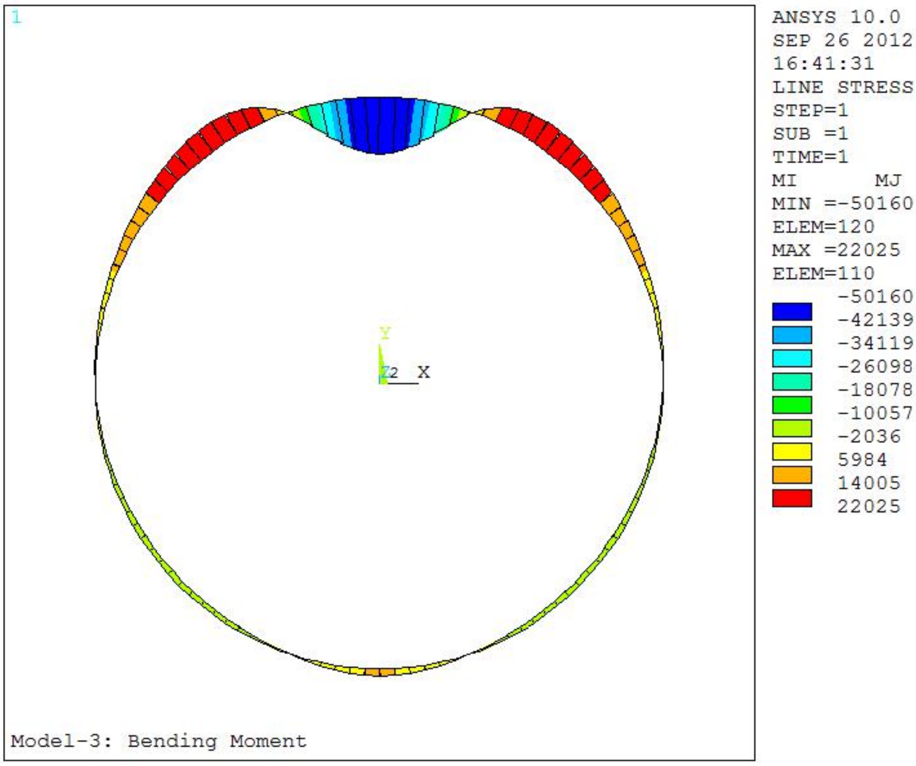

Figure 7. Design Model Model-3: Moment Diagram

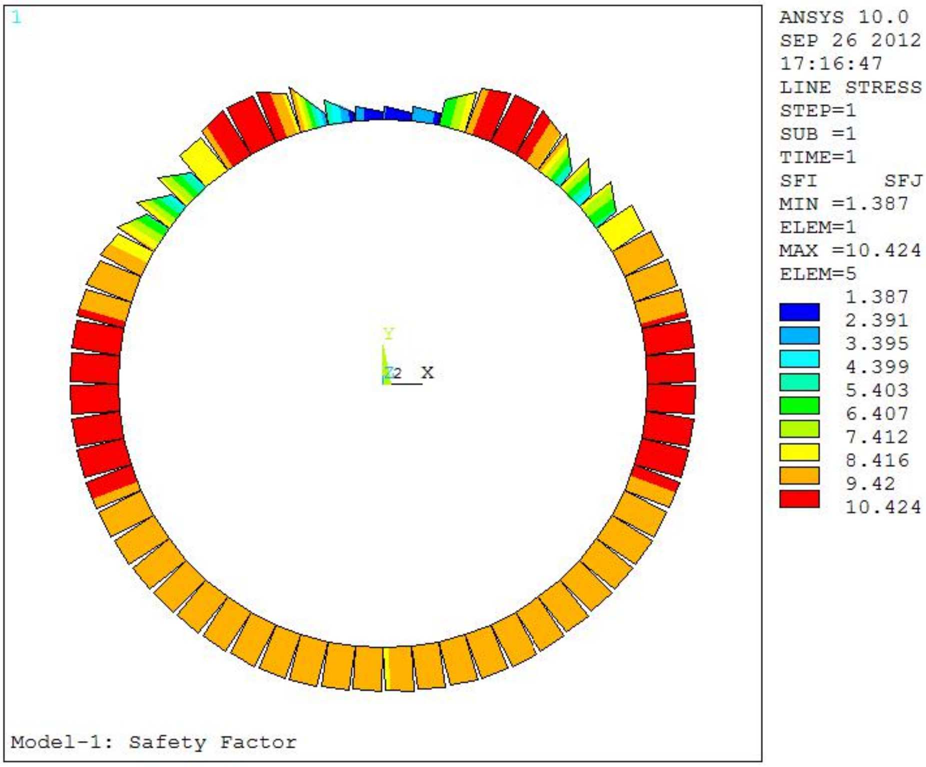

Figure 8. Design Model Model-1: Safety Factor

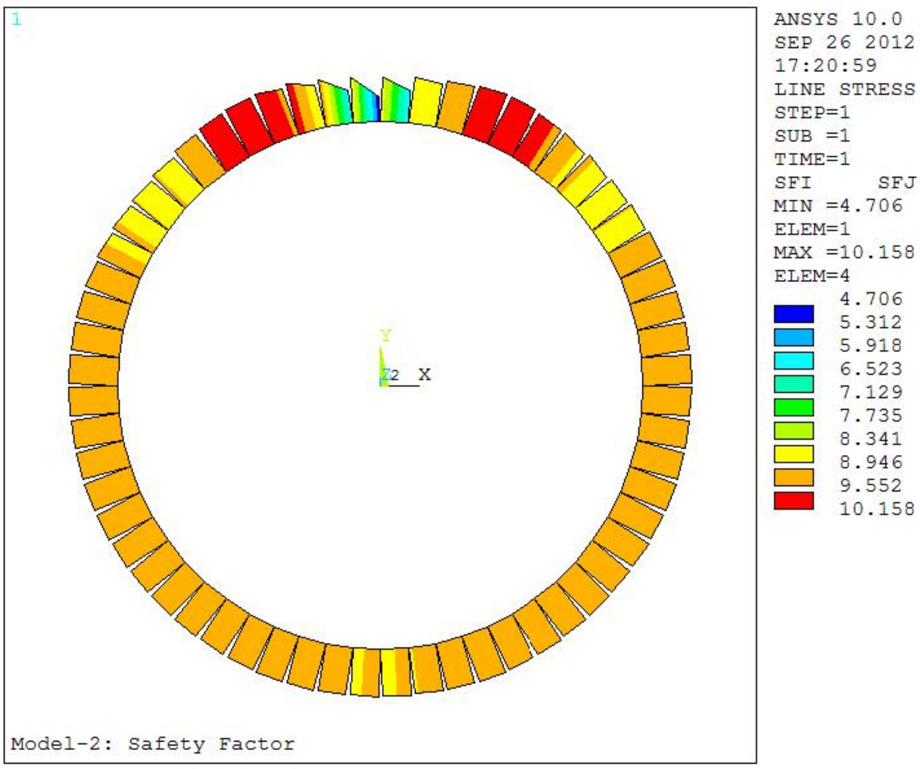

Figure 9. Design Model Model-2: Safety Factor

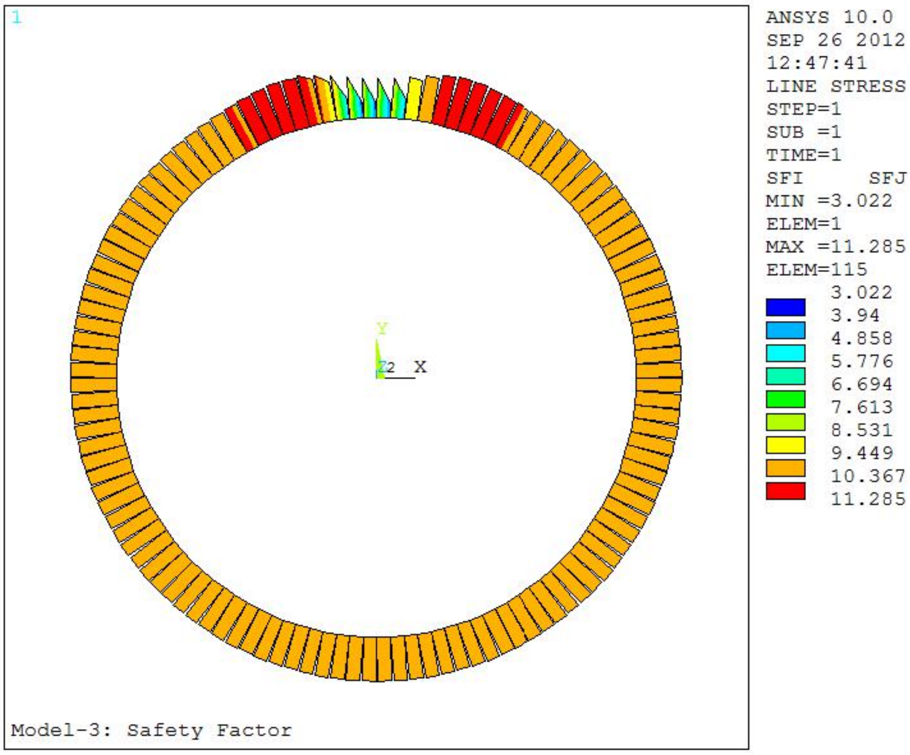

Figure 10. Design Model Model-3: Safety Factor

Compared with the calculation results of this example: the maximum bending moment and the minimum safety factor of the three models are located in the vault, and the model Model-1 is the most conservative design, with the maximum bending moment value of-73.4kN·mand the minimum safety factor of 1.4. Model Model-2 has a maximum bending moment of -47.2kN·mand a minimum safety factor of 4.7. Compared with Model-1, the maximum bending moment value of Model-2 is reduced by about 35%, and the minimum safety factor is increased by about 240%. It can be seen that the bending moment is reduced when tangential spring is used. It is recommended that the tangential spring unit is only available when the two types of models backfill compaction grouting. The model Model-3 has a maximum bending moment value of -50.0kN·m at the vault, which is basically the same as Model-2. The bending moment value outside the model Model-3 lining arch is about 50% less than the model Model-2 and the bending moment distribution is more uniform, which is related to the influence of the joint on the lining stiffness. The minimum safety factor value 3.2 of the Model Model-3 is about 32% lower than the Model Model-2, which indicates that the joint unit has a certain adverse effect on the safety of the lining structure. It can be seen from the calculation results that the Model Model-3 reflects the influence of the joint on the lining structure and is more in line with the actual deformation of the segment.

3. Inversion Analysis of the Action Load

The axial force and bending moment of the tube with easy measurement and high accuracy were selected as the back analysis sample data, and the inversion analysis model was established, including the calculation model of the inversion analysis, the establishment of the optimization analysis objective function and optimization method for inversion analysis.

3.1 Computational model of inversion analysis

The lining segment structure design model uses the beam-joint deformation discontinuity model (Model-3), which is closer to the actual lining structure. The earth pressure load distribution acting on the lining structure is assumed to be a linear distribution, and the actual earth pressure distribution is mostly nonlinear. In order to make the load linear expression more realistic, this paper increases the conventional 4-section earth pressure expression to 8 segments (up and down, left and right, respectively divided into two sections), and rejects the assumption of the left-right symmetry of the load in the conventional method. The computational model of the inversion analysis is shown in Figure 11.

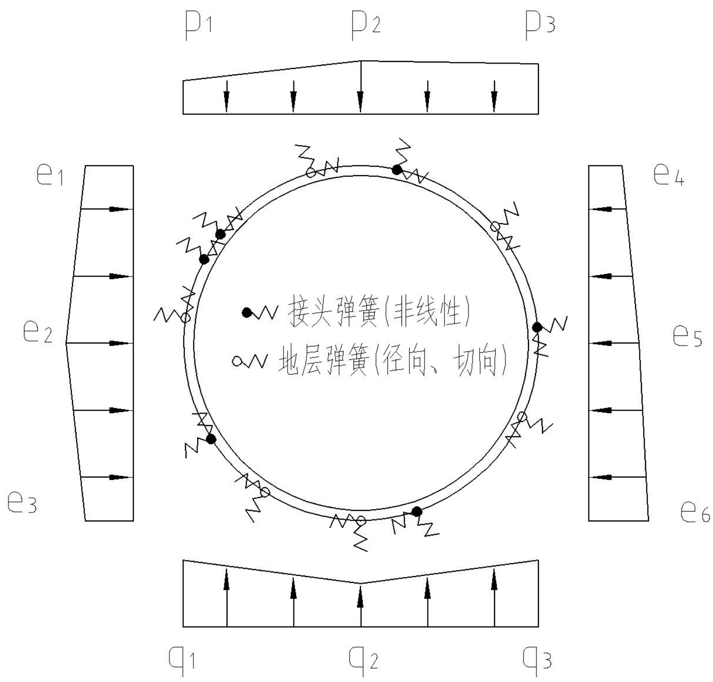

Figure 11. Inversion analysis calculation model

接头弹簧（非线性）：Joint spring (non-linear)

地层弹簧（径向 切向）：Formation spring (radial，tangential)

3.2 Optimization solution for inversion analysis

In the tunnel construction of shield tunneling, the strain (stress) measurement of the segment steel bar has high precision and reliability. Therefore, the field measurement of the axial force and bending moment of the segment is used for the inversion calculation. Assuming that the unknown is the parameter in the load component p_i , q_i , (i =1, 2, 3, 4, 5, 6), the optimization objective function is established J : [3,4]

$$J(p,q)=\frac{\omega_1\sum_{i=1}^{L_1}\left(N_i-N_i^*\right)^2}{\sum_{i=1}^{L_1}N_i^2}+\frac{\omega_2\sum_{i=1}^{L_2}\left(M_i-M_i^*\right)^2}{\sum_{i=1}^{L_2}M_i^2}$$

Where: L_1 , L_2 indicates the number of points of the axial force and bending moment of the lining structure; N_i , M_i is the calculated value of the internal force; N_i^* , M_i^* is the measured value of the internal force; ω_1 , ω_2 is the corresponding weighting coefficient, usually taken $\omega_1=\omega_2=1$.

The objective function J obtains the minimum value, which means that the assumed distribution earth pressure is the closest to the actual force of the structure. In order to make the objective function obtain the minimum value, the zero-order optimization method provided by ANSYS is used here. The zero-order method is a general-purpose perfect method. The solution is not easy to fall into the local minimum solution and is suitable for most engineering problems. The zero-order method [11] has two key points in the solution process: 1. The program uses curve fitting to establish the relationship between the objective function and the design variables, the essence of which is the least squares method; 2. The program will constrain the problem (state variable and the design variable set the value range). The method of approximating the penalty function of the objective function is included in the added constraint and replaced with the unconstrained problem, so that the optimization method is more efficient.

3.3 Inversion analysis example

The engineering examples in Section 3.2 are still used here. The measurement data in the inversion analysis calculation, including the axial force N and the bending moment M of the segment, can be obtained in the field measurement. The steel stress meter and the axial force meter are buried in the same position. Figure 12 shows the arrangement of the force measurement in the tunnel structure.

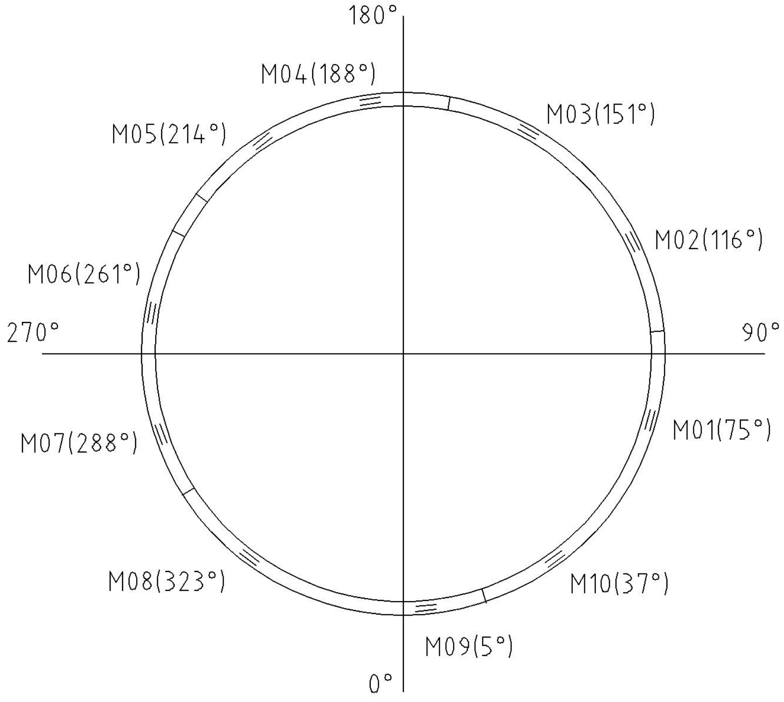

Figure 12. Arrangement of measuring points for steel stress gauges and axial force gauges

Table 2. Measured and inverted calculation of axial force of lining segments

Measuring point	Axial force /kN	
	Measured value	Inversion value
1	-527	-641
2	-415	-661
3	-519	-745
4	-454	-744
5	-503	-632
6	-322	-570
7	-620	-564
8	-701	-662
9	-610	-688
10	-505	-577

Table 3. Measured bending moments and inversion bending moments

Measuring point	Bending moment /(kN·m)	
	Measured value	Inversion value
1	-31	-9
2	-20	11
3	-2	-13
4	5	9
5	8	2
6	-29	-14
7	2	-2
8	1	8
9	19	3
10	-24	-10

Table 4. Initial and inversion values of the design load

Load variable	Design initial value/(kN/m^2)	Inversion calculation/(kN/m^2)
p_1	203	183
p_2	203	112
p_3	203	176
e_1	161	157
e_2	193	139
e_3	224	59
e_4	161	105
e_5	193	53
e_6	224	118
q_1	210	184
q_2	210	132
q_3	210	161

The measured values and inversion calculation values of the segments and axial forces and bending moments are shown in Table 2 and Table 3. The results show that the measured values and inversion values of axial force and bending moment are consistent. The inversion axial force is about 25% larger than the measured axial force, and the two are basically consistent in terms of numerical values, but there are some differences in the numerical change trend. The measured value and the inversion value of the bending moment are basically close in the numerical change trend, but there is a certain difference in the numerical value.

Table 3 shows the design initial values and inversion calculations for the load components acting on the lining structure. Except for e_3 and e_5, the difference between the inversion value and the initial value of the design is not obvious, but the distribution of the two is obviously different. According to the design initial value, the maximum bending moment value of the segment is -50 kN·m, and the minimum safety factor is 3.0. According to the inversion load, the maximum bending moment value is -24 kN·m, and the minimum safety factor is 10.6. The comparison shows that the initial design of this example can meet the safety requirements, but it is too conservative. The initial design load and the inversion load are respectively calculated in the initial calculation and the inversion calculation. The calculated bending moment and the calculated safety factor of the two are shown in Fig. 13, Fig. 14 and Fig. 15, Fig. 16 respectively.

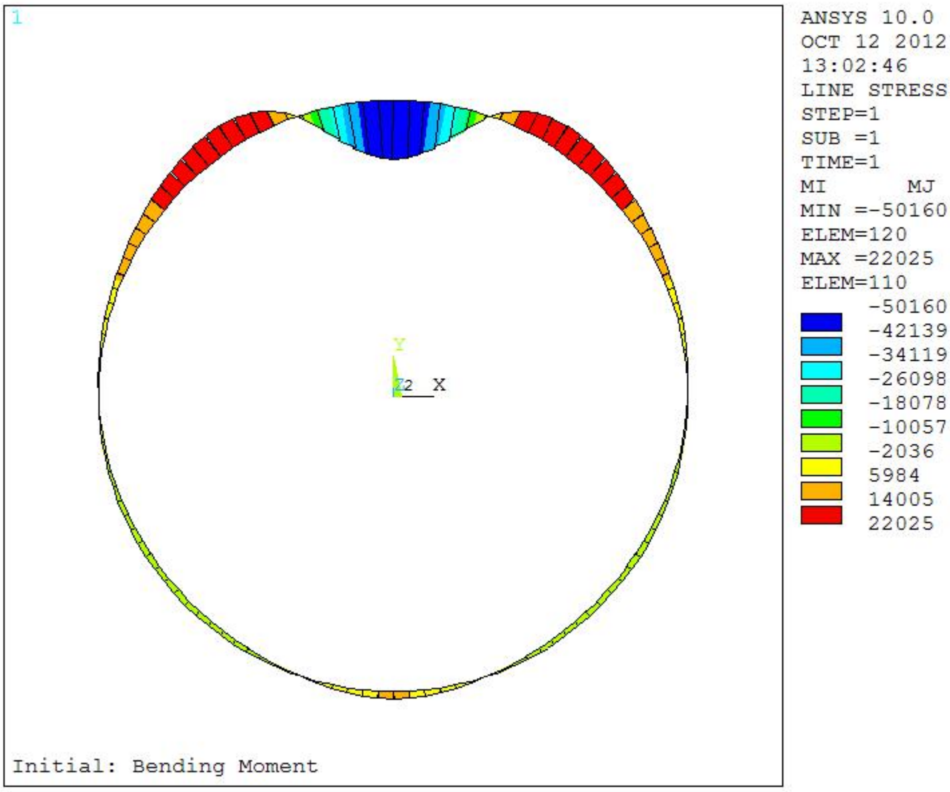

Figure 13. Initial calculated moment diagram

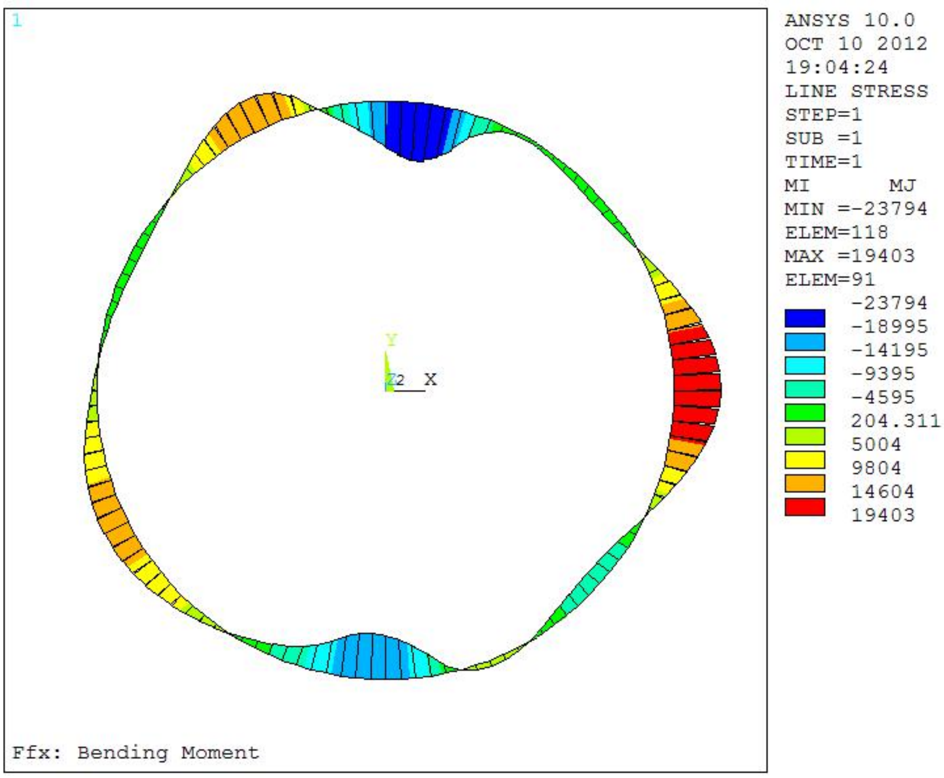

Figure 14. Inversion of the calculated moment diagram

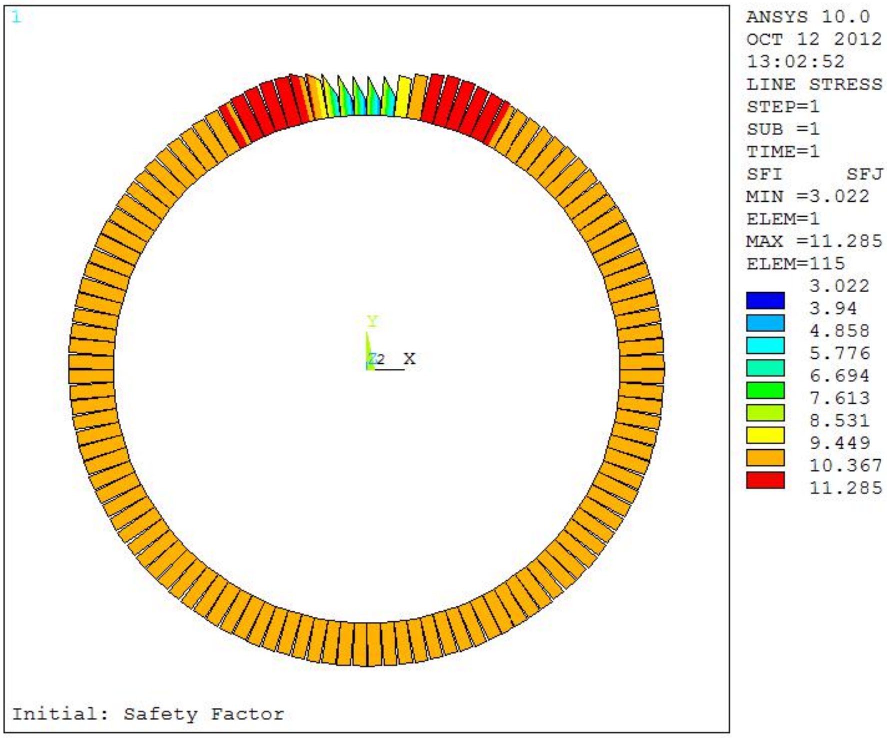

Figure 15. Initial calculated safety factor

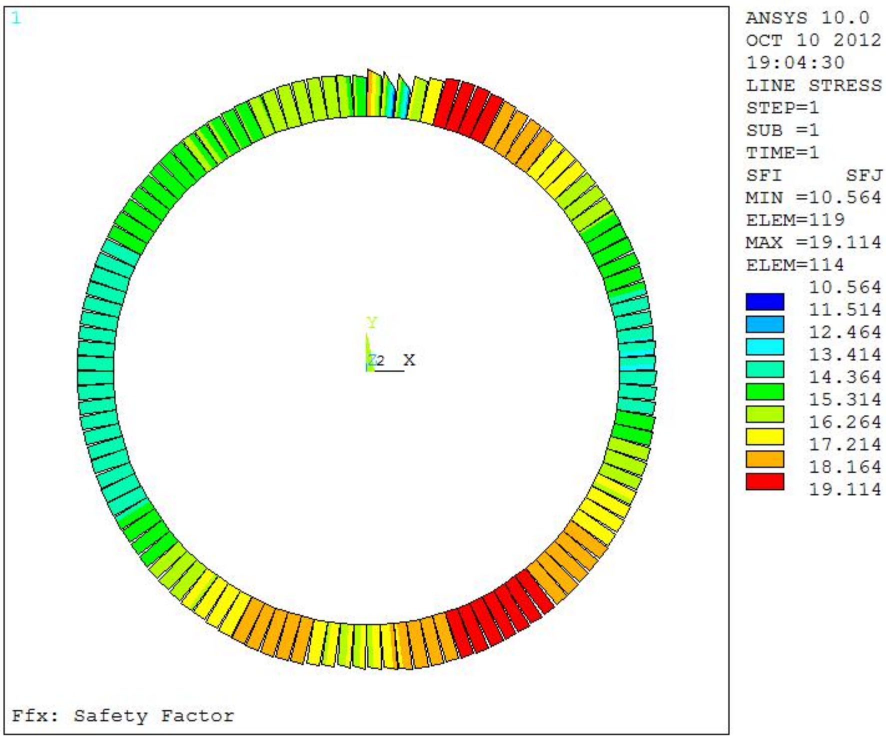

Figure 16. Inversion of the calculated safety factor

4. Conclusion

4.1 The tangential springs in the beam-spring model and the beam-joint model have a significant influence on the internal forces of the structure. The two types of models suggest the use of tangential spring units only in the case of grouting backfill compaction.

4.2 The beam-joint model (considering nonlinear) can well simulate the influence of joints on the deformation of the segment lining, but the model is mostly implemented by self-programming. This paper implements the program with general finite element software, which provides a simple and practical method for shield lining calculation.

4.3 Based on the beam-joint deformation discontinuity model, the earth pressure load distribution and size acting on the lining structure are analyzed inversion. The actual example shows that the inversion is effective and can be used for information feedback design.

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