Influence of the Viscose's Properties on Load-carrying Properties of Water Conveyance Tunnel Strengthened with Steel Plate

Gan QIN[1,a], Shen-Grong CAO[1,b,*]

[1]State Key Laboratory of Water Resources and Hydropower Engineering Science (Wuhan University), Wuhan, China

[a]gqin@whu.edu.cn, [b]shrcao@whu.edu.cn

*Corresponding author

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Abstract: An overall three-dimensional finite element model has been established to simulate the high pressure water conveyance tunnel lining strengthened with steel-bonded reinforcement method. This model is used to analyze the mechanical characteristics of steel plate pasted on the inner surface of the lining concrete. Influence of the ratio of viscose's elasticity modulus to thickness on the stress transferred from steel plate to concrete is analyzed. The hoop stress of lining concrete and steel plate under the conditions of different ratios of viscose's elasticity modulus to thickness is also studied. The analyses show that the internal water pressure undertaken by steel plate decreases and the internal water pressure undertaken by concrete increases when the ratio of viscose's elasticity modulus to thickness (E/T) increases. Using the viscose with smaller ratios of elasticity modulus to thickness can increase the utilization of steel plate and improve the stress condition of lining concrete. Changes in the ratio of viscose's elasticity modulus to thickness has a great influence on the stress of steel plate and concrete lining when E/T is less than or equal to 10 N/mm^3, and changes in the ratio of viscose's elasticity modulus to thickness has a small influence on the stress of steel plate and concrete lining when E/T is greater than 10 N/mm^3. In the design of steel bonded structure, we suggest using the viscose which the ratio of elastic modulus to thickness is less than 10 N/mm^3.

Introduction

The high pressure water conveyance tunnels are usually buried underground, where the geological environments and hydraulic conditions are complicated. Defects like deterioration failure and aging degradation can easily occur after a period of operation [1]. Examples can be given as follow. Issues like lining cracks and damages to baseboard occurred in some tunnels of Dongjiang Water Resources Project after a period of operation. In Water Diversion Project from Luanhe River to Tianjin City, after 17 years of operation from 1983 to 2000, masses of white soluble substances dissolved out from the surface of the lining concrete. There also occurred defects like lining cracks, pitted surface, serious seepage dots, leakage in expansion joints, etc. Without timely mending and strengthening, the tunnels may collapse and the pipelines can settle, which will seriously threaten the safety of the engineering projects [2]. Thus, as for the defects, it is essential that economical, reasonable and practical reinforcement measures be adopted.

There are reinforcement measures like concrete spraying, substitute of vault, arch covering, groove embedding and steel inserting, steel arch strengthening, double liquid grouting, etc. However, some constraints can never be ignored in these methods. They may influence the clearance of the tunnels, improve the maintenance cost, prolong the maintenance time and cause disturbance to the surrounding rock and hydraulic structures [3]. With the advantages of convenient and fast construction, causing little influence to the dead weight and external dimension, significant enhancement of stiffness and load capacity, the steel-bonded reinforcement method has a wide application prospect.

At present, the steel-bonded reinforcement method is mainly adopted in improving girders' bending stiffness and steer strength [4]. Even in tunnel projects, it's only implemented in issues concerning increasing the anti-instability using bonded steel [5]. Therefore, as an indispensable component, the concept steel-bonded reinforcement has not been studied thoroughly, revealing the impact of sticky steel glue's material attributes to the structure's load behavior and the loaded property between all parts. Thus, using finite element method, this article has carried out the simulation of the steel-bonded reinforcement method. It mainly analyzed the impact of different ratios of viscose's elastic modulus to thickness on the stress transferred from steel plate to concrete. Additionally, it summarized the varying pattern of the hoop stress of lining concrete and steel plate. All the researches were conducted hoping that the results can serve as reference provision for the designing and construction of high pressure water carriage tunnels adopting the steel-bonded reinforcement method.

Theoretical Analysis on the Force Transmission Effect of Viscose

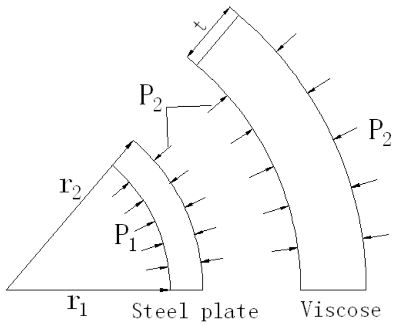

Fig. 1 Schematic Diagram of Differential Segment Calculation

Select the vertical section and assume it as full elastic plane problems with regardless of the material weight. The force transmission effect of viscous damping structure was calculated to analysis the force transmission effect of the composite structure after the tunnel was strengthened by steel plate. Calculating diagram is shown in figure 1 where E_1 is elastic modulus of steel sheet, μ is poisson's ratio, r_1 is inner diameter of the steel plate, r_2 is outer diameter of the steel plate, E_2 is elastic modulus of the viscose, t is thickness of the viscose, P_1 is internal pressure, P_2 is radial pressure from viscose to the lining concrete.

According to the Lamei Formula, the hoop stress of the steel plate outer surface can be expressed by:

$$\sigma_\theta = \frac{r_1^2 p_1 - r_2^2 p_2}{r_2^2 - r_1^2} + \frac{(p_1 - p_2) r_1^2}{r_2^2 - r_1^2} \tag{1}$$

The hoop strain of the steel plate outer surface can be expressed by:

$$\varepsilon_\theta = \frac{\sigma_\theta}{E_1} + \mu \frac{p_2}{E_1} \tag{2}$$

The radial deformation of the steel plate outer surface can be expressed by:

$$\Delta_r = r_2 \varepsilon_\theta \tag{3}$$

The viscose compression amount equal to the radial deformation of the steel plate outer surface, so the stress pass from viscose to the lining concrete can be determined by:

$$P_2 = E_2 \frac{\Delta_r}{t} \tag{4}$$

The stiffness of viscose can be given by:

$$k = \frac{E_2}{t} A \tag{5}$$

According to the above formula we have:

$$\left(\frac{2r_1^2}{r_2^2-r_1^2}\times\frac{p_1}{p_2}-\frac{r_1^2+r_2^2}{r_2^2-r_1^2}+\mu\right)\times\frac{r_2}{E_1}\times\frac{k}{A}=1 \tag{6}$$

Equation (6) shows that, when the inner diameter and the outer diameter of the steel is known, the stress P2 from viscose to the lining concrete relates only to E2/t. So the ratio of elastic modulus and thickness of viscose can determine the force transmission effect of the structure and then determine the stress distribution of the lining concrete. The ratio of viscose's elastic modulus to thickness which are 0.01N/mm3, 0.1 N/mm3, 1 N/mm3, 10 N/mm3, 50 N/mm3, 100 N/mm3, 500 N/mm3, 1000 N/mm3, 3000 N/mm3 are selected as analysis object respectively to show the impact of the steel plate and concrete lining stress due to changes in the structural properties of viscose.

Calculation Condition

The diameter of the tailrace tunnel in a pumped storage power station is 3.2m, and the thickness of the reinforced concrete lining which is poured with C30 concrete is 0.4m. The lining is under about 0.5MPa internal water pressure when the pumped storage power station runs. Due to the dig of road tunnel which is beyond the tailrace tunnel, the overlying rock mass on the tunnel will be not thick enough, and then crack will appear. In order to prevent from this situation, 6 mm thick steel plate will be bond on the internal surface of reinforced concrete lining with the hydrophilic epoxy resin, which will strengthen the lining structure and heightening seepage-prevention. The sketch maps of lining strengthening structure are showed below in Fig.2 and Fig. 3.

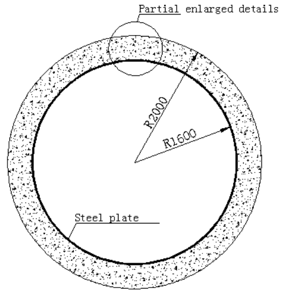

Fig. 2 Cross Section of Strengthening Structure of Tailrace Tunnel

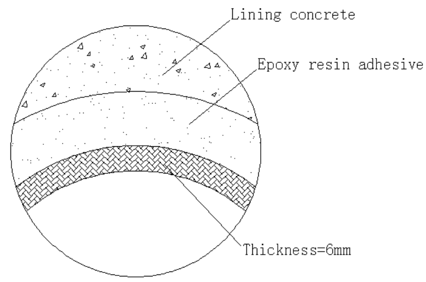

Fig. 3 Partial Enlarged Details of Tailrace Tunnel

Calculation Model

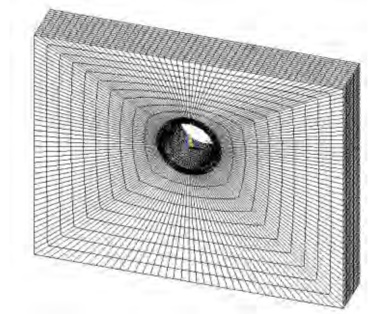

Fig. 4 The Finite Element Mesh of the Whole Model

Take a 3.0m long tunnel lining along with peripheral foundation to establish the overall model, and use the entity elements to simulate viscose, which are convenient to reflect some parameters straightly, such as Modulus of Elasticity and Poisson's ratio. SHELL 63 elements are used to simulate steel lining. Boundaries are divided into surface elements with mesh map, and then the sweep meshing method is used to generate the body element by sweep the whole model from the boundary surface mesh. The mesh for model calculation is showed in Fig.4. The concrete lining is divided into fifteen layers along the longitudinal direction and 10 layers along the radial direction. The entire model elements are totally 448680.

Simulation Results

Effect of the Ratio of Viscose's Elastic Modulus to Thickness on the Stress Transmission from Internal Water to Concrete though Steel Plate

In order to compare the effect of different viscose elastic modulus/thickness ratios on bearing capacity of viscose materials, several E/T are simulated in this paper. The E/T is assumed as follows: $0.01N/mm^3$, $0.1N/mm^3$, $1N/mm^3$, $10N/mm^3$, $50N/mm^3$, $100N/mm^3$, $500N/mm^3$, $1000N/mm^3$, and $3000N/mm^3$. The results of average hoop stress increment and water pressure outward transfer ratio of steel liner and lining concrete have been obtained and listed in Table 1.

Tab. 1 Average Hoop Stress and Water Pressure Outward Transfer Ratio of Steel Liner and Lining Concrete in Different Viscose E/T Ratios

Ratios of viscose's elastic modulus to thickness(N/mm^3)	Average hoop stress increment of lining concrete(MPa)	Average hoop stress increment of steel plate(MPa)	Water pressure outward transfer ratio(%)
0	0	132.729	0
0.01	0.097	130.225	1.89
0.1	0.247	111.309	16.14
0.5	0.580	69.622	47.546
1	0.742	49.374	62.80
10	1.011	15.507	88.32
50	1.046	11.095	91.64
100	1.050	10.521	92.07
500	1.053	10.052	92.43
1000	1.052	9.985	92.48
3000	1.048	9.916	92.53

As can be seen from the calculation results, with the increase of E/T, the water pressure transferred to lining concrete increased. Namely the internal water pressure borne by the steel plate reduced gradually but the pressure borne by lining concrete increased at the same time. This shows that with the increase of E/T, the water pressure borne by steel liner decreases and is mainly borne by lining concrete. So the use of viscose with smaller E/T can improve the utilization rate of steel plate and improve the stress condition of lining concrete.

At the same time, when E/T is Less than or equal to $10N/mm^3$, the change of E/T has big influence on the bearing ratio of the component materials. However, when E/T is greater than $10N/mm^3$, the influence of E/T on bearing ratio tends to be small. Thus, increasing the E/T to improve the concrete stress condition can not meet expectation when the E/T is greater than $10N/mm^3$. Therefore, the influence of the elastic modulus and thickness of viscose on structure stress should be considered comprehensively. Choose viscose materials with E/T less than $10N/mm^3$ to reduce the internal water pressure borne by lining concrete is the recommended method.

Effect of Viscose E/T Ratios on Stress Distribution

In order to compare the influence of different ratios of viscose's elastic modulus to thickness on hoop stress distribution of lining concrete and steel plate, the E/T of $0.01N/mm^3$, $0.1N/mm^3$, $1N/mm^3$, $10N/mm^3$, $50N/mm^3$, $100N/mm^3$, $500N/mm^3$, $1000N/mm^3$, $3000N/mm^3$ were simulated. The simulation results are shown in Fig.5 and Fig.6.

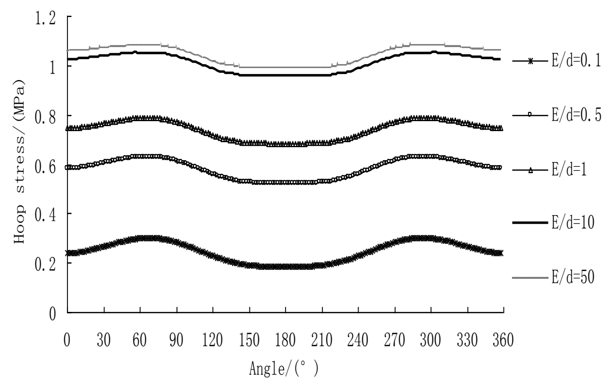

Fig. 5 The Hoop Stress Distribution of Lining Concrete under the Condition of different E/T Ratios

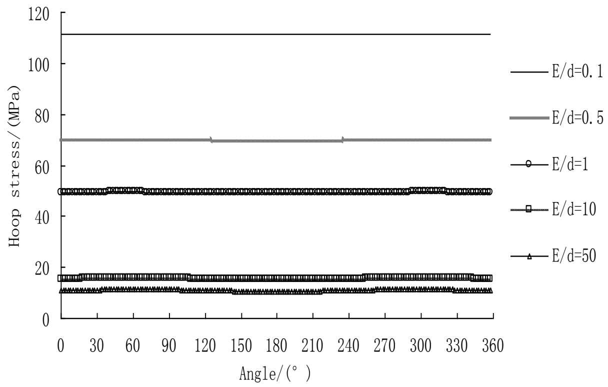

Fig. 6 The Hoop Stress Distribution of Steel Plate under the Condition of Different E/T Ratios

From the calculation results shown in Fig.5 and Fig.6, the E/T have little influence on stress distribution of lining concrete and steel plate. The stress distribution is basically consistent in different E/T. However, with the increase of E/T, the hoop stress of lining concrete increased gradually, but the hoop stress of steel liner reduced. The reason of this phenomenon is that the steel plate had lager expansion deformation under internal water pressure in the cases of small E/T. Namely, most of the internal water pressure was borne by steel plate, thus reducing the stress transferred to lining concrete. The analysis above further verifies the conclusion in 4.1.

Conclusion

According to the characteristics of high pressure water conveyance tunnel's steel-bonded strengthened structure, this paper studies the stress transferring mechanism between steel plate and concrete. The main research conclusions and related suggestions are as follows:

(1)When designing bonded steel structure, the influences to structure performance caused by viscose's elasticity modulus and thickness should be both considered. Setting the ratio E/T of viscose's elasticity modulus to thickness as design reference is suggested.

(2)With the increase of the ratio of viscose's elasticity modulus to thickness, internal water pressure transmits to steel lining is reduced gradually; internal water pressure transmits to concrete is increased gradually. Thus, small E/T can raise the utilization of steel and improve the stress condition of the lining concrete.

(3)E/T is equal to 10N/mm^3 as boundary, as E/T is Less than or equal to 10 N/mm^3, the influence to materials' bearing ratio cause by the changes on the ratio of viscose's elasticity modulus to thickness is significant; as E/T is greater than 10 N/mm^3, the influence is small. We suggest that the E/T shall less than 10 N/mm^3 when design steel plate structure in high pressure water conveyance tunnel.

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