Optimization design of transition connection between prestressed lining and steel-concrete composite lining in high water pressure tunnels

Abstract:

The Pearl River Delta Water Resources Allocation Project aims to solve the water conflict in this area and ensure the water use in water scarce areas and eastern Guangdong. The water conveyance tunnel project adopts a multi-layer lining structure to improve the bearing and deformation capacity of the structure due to its deep burial, high internal water pressure, and many cross domain areas. Due to the long distance and cross basin nature of the project, considering factors such as surrounding rock and external loads, multiple lining methods were chosen to achieve it, including steel concrete lining and prestressed lining.

Keywords: tunnel; concrete; construction

1 Introduction

When working in hydraulic tunnels, it is necessary to withstand high internal water p ressure, and the structure often requires high impermeability performance. In the past, tradi tional hydraulic tunnels often used steel plate lining as a structural form[1,2]. In the 1970s and 1980s, European countries such as Germany began to use prestressed concrete lining as a new type of structure to replace traditional steel plate lining structures. Steel lined r einforced concrete pressure pipes have been a rapidly developing new structural form in C hina in recent years. In the mid-1980s, China first applied it to the Dongjiang and Jinshui tan hydropower stations, achieving significant technical and economic benefits. After furthe r argumentation, 26 pressure pipelines with a diameter of 12.4 meters in the Three Gorges Hydropower Station have all adopted steel lined reinforced concrete structures, which is a great leap. Reinforced concrete pipes are not only economical but also safe. Because com bining steel lining and reinforced concrete, two materials with vastly different properties, a nd taking appropriate safety measures, greatly reduces the risk of catastrophic accidents ca used by the simultaneous destruction of both. This is also the main factor in adopting the joint stress scheme in the Three Gorges Project.

Tunnel engineering can generally be divided into two types: pressure tunnel and non pressure tunnel. Compared to non pressure tunnel, the lining of pressure tunnel still needs to bear internal water pressure in addition to supporting function. When the internal press ure reaches a certain level, the lining structure will lose its ability to continue bearing, an d the study of its internal pressure bearing performance is extremely important. According to the division of layers, there are generally three types of lining in existing pressure shi eld tunnel engineering: single layer lining, double layer lining, and three-layer lining, ordinary concrete lining, and prestressed concrete lining. This article mainly studies the connection problem between steel pipe lining and prestressed lining in pressure tunnels.

2Steel pipe lining

Steel has good mechanical properties such as tensile and compressive strength, while also avoiding the problem of "easy cracking" of concrete materials. Steel pipes made from it can be used for high internal pressure water transportation, and the lining diagram is shown in Figure 1. The steel pipe lining is usually made of prefabricated steel pipes for assembly inside the tunnel, so a certain space is often reserved between the pipe segments and filled later. The filling medium can be self compacting concrete (SCC) with good fluidity. There are usually two ways to fill self compacting concrete, with and without a cushion. The existence of an isolation cushion layer can separate the pipe segment from the steel pipe to bear external loads and internal pressures. A typical case of this separate load-bearing structure is the Xijiang Water Diversion Project [3,4]; Another kind of lining structure without cushion is completely filled with SCC between steel pipes and segments, which has good pressure transmission performance. A typical case of this kind of joint stressed structure is the the Pearl River Delta water resources allocation project under construction[5].

3 Prestressed concrete lining

In water conservancy and hydropower projects, hydraulic pressure tunnels are one of the most common diversion structures. Pressure tunnels usually adopt circular sections and are mostly lined. During operation, the lining and surrounding rock work together to withstand various internal and external pressures [6-7]. For the design of hydraulic pressure tunnels, it is mostly necessary to consider the stability of the tunnel surrounding rock and the leakage of internal and external water. There are various ways of tunnel lining, among which the widely used is the steel plate reinforced concrete combined lining [5], which has relatively mature construction design experience. However, due to the low tensile strength of concrete materials, once the ultimate tensile strain is exceeded, cracking will occur. Therefore, in large structures and structures with strict requirements for crack level, pure reinforced concrete is not suitable. In this case, prestressed concrete structures have emerged [8]. Prestressed concrete structures are pre applied with compressive stress opposite to tensile stress in concrete, which can greatly improve the working performance of concrete and make the application range of concrete structures increasingly broad. With the continuous development and innovation of construction technology and building materials, high-pressure grouting concrete lining and prestressed concrete lining have emerged [9].

4 Finite element simulation

4.1 Calculation range and displacement boundary conditions

(1) Coordinate system conventions

Using the overall cylindrical coordinate system, it is agreed that the water flow direction is the forward direction of the Z-axis, R is the radial direction of the tunnel, and T is the circumferential direction of the tunnel. The origin of the coordinate axis is located at the center of the circle with a longitudinal coordinate of 0.

(2) Calculation Scope Impact

The calculation range of the overall soil structure of the tunnel is -16 m~16 m in the X direction; Take -24.85 m~20.85 m in the Y direction; Z-axis 0 m~16.64 m. According to relevant literature, if the surrounding rock exceeds 5 times the tunnel diameter, the impact on the lining is negligible [10]. The scope of consideration for soil foundation can include areas of structural stress and deformation.

(3) Displacement boundary conditions

The surrounding rock element constrains the displacement in the Y direction of the bottom surface, the displacement in the X direction of the side surface, and the displacement in the Z direction of the longitudinal plane. The backfilling of the sealing joint with polyethylene constrains the Z-direction displacement, and the lining surface is considered as a free boundary. The model constraints are shown in Figure 1.

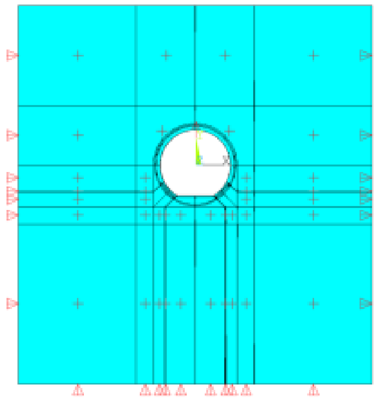

Fig. 1 Model constraint diagram

4.2 Unit selection and grid division

The finite element model mainly includes lining concrete, prestressed steel strands, anchor slots, waterstops, and corresponding soil foundations. The soil, lining, and anchor groove are all modeled using three-dimensional solid elements, while the prestressed steel bars are modeled using rod elements, taking into account the material nonlinearity of the soil. The mesh generation is based on the stress characteristics of the lining structure, and the mesh is encrypted in key parts to ensure a high degree of consistency between the model and the actual project. The type and number of unit divisions are shown in Table 1.

Table -1 The mesh of finite element model for tunnel

Structural parts	Unit Type	Number of units
Inner lining concrete	3D solid units SOLID185	125200
Post pouring concrete for anchor groove	3D solid units SOLID185	3280
Prestressed steel reinforcement	Rod unit LINK180	5210
surrounding rock	3D solid units SOLID185	560420
steel lining	Shell unit SHELL181	1400

4.3 Load application

The solid modeling method is used to simulate the interaction between lining and surrounding rock by coupling the nodes of prestressed steel bars and concrete. Simulate ordinary steel bars by defining the real constant of concrete unit reinforcement ratio. The tensioning pre-stress is applied through a special program using the cooling method. The effective tensioning pre-stress along the route is calculated, and the temperature drop value is calculated according to formula (3.1). It is applied to the i and j points of the prestressed tendon element, and different temperatures cause shrinkage deformation of the element to generate tensile stress.

$$\Delta T = \frac{F}{\alpha EA} = \frac{\sigma_{Pe}}{\alpha E} \qquad (3.1)$$

式中：Δ□—Temperature reduction of prestressed reinforcement unit（℃）；

□—Tensioning value of prestressed reinforcement（kN）；

□—Linear expansion coefficient of prestressed reinforcement；

□—Elastic modulus of prestressed reinforcement（MPa）；

□—Cross section area of prestressed reinforcement（mm^2）

4.4 Load and working condition combinations

4.4.1 Calculating Load

(1) Surrounding rock pressure

vertical direction

$$\mathbf{q_v = (0.2 \sim 0.3)\gamma_R b} \qquad （4.2）$$

horizontal direction

$$q_h = (0.05\sim0.10)\gamma_R h \quad (4.3)$$

In the equation:

v—Vertically distributed surrounding rock pressure, kN/m^2

h—Horizontal uniformly distributed surrounding rock pressure, kN/m^2

r—Bulk density of rock mass, kN/m^3

b—Tunnel excavation width, m

h—Tunnel excavation height, m

When calculating the rock pressure in this article, the rock pressure value is calculated by substituting the excavation width and height values into the above formula according to the engineering design. The rock load is applied in the form of surface effect elements in ANSYS software.

(2) Structural self weight

The self weight of the structure is determined according to equation (4.4):

$$G_i = \gamma_m \times V_i \quad (4.4)$$

In the equation:

G_i——self-weight (KN);

γ_m ——Structural material weight (kN/m^2);

V_i ——Corresponding volume of structural materials (m^2).

(3) External water load

The external water pressure is determined according to the "Design Specification for Hydraulic Tunnels" (SL 279-2016) [64] and equation (4.5):

$$P_e = \beta_e \gamma_w H_e \quad (4.5)$$

In the equation:

P_e ——external water pressure (MPa);

β_e ——Reduction coefficient of external water pressure. When there is an internal water combination, the smaller value should be taken; When there is no combination of internal water, β _ E should take the maximum value;

γ_w —— The weight of water, using 9.81 kN/m^2 ;

H_e ——The acting head from the groundwater level line to the center of the tunnel, and the internal water pressure is taken when the internal water seeps out.

4 Summary and conclusion

This study proposes an optimized design scheme for the transition connection between prestressed lining and steel-concrete composite lining of high water pressure tunnels, and analyzes and evaluates the optimized design scheme. The following conclusions are drawn:

(1) The finite element calculation results of the lining structure during the construction, operation, and maintenance periods were analyzed, and it was determined that the full section of the lining inner surface was under pressure when the prestressed tensioning was completed during the construction period. The maximum tensile stress on the lining inner surface during the construction completion stage was 1.48 MPa, and the full section of the lining inner surface was under pressure during the operation period. The circumferential compressive stress on the lining surface during the maintenance period was 11.45 MPa. The feasibility of the optimized design scheme has been verified by the fact that the concrete lining is not subject to tensile cracking or crushing.

(2) Analyzed the stress patterns of the lining in each step of the prestressed tensioning sequence during the construction period, and clarified that the longitudinal tensile stress of the adjacent ring prestressed steel strand lining structure exceeds the design value of the concrete tensile strength. Staged tensioning can reduce the gradient of stress changes in the lining concrete during the construction tensioning process, in order to meet the crack resistance requirements of prestressed concrete lining. An optimized tensioning sequence for prestressed steel strands is proposed to solve the problem of continuous tensioning prestressed steel strand concrete lining cracking.

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