Comparative Investigations on Internal Force Distribution Characteristics on Concrete Segments in Qiongzhou Strait Sub-Sea Tunnel

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Abstract. In the design of shield tunnel concrete segments, the calculation of internal forces on segment sections is an important part. In order to study the influence of combining calculation of water and soil pressure and separate calculation of water and soil pressure towards internal forces on segment sections, taking the Qiongzhou Strait sub-sea tunnel as the background, ANSYS software is used to establish the equivalent stiffness circle model, hinged model and beam spring model, and the internal forces on segment are calculated by two methods of combining calculation of water and soil pressure and separate calculation of water and soil pressure. The results show that the difference of the bending moment between the two methods is great while the difference of the axial force is small, the maximum bending moment of combining calculation of water and soil pressure is 2.2~2.9 times larger than that of separate calculation of water and soil pressure, and the axial force is 11%~16% larger than separate calculation of water and soil pressure.

1. Introduction

With the economic development and increasement of people living level, the demands for transportation infrastructures increase daily. Metro tunnel and underwater tunnel have been widely constructed by means of shield machine in worldwide because shield tunneling has some advantages of safety operations, lower effects on environments, high applicable for soil layers and higher operating speed. The concrete segments are used to support loading from soil and water pressure. There some segments in a lining ring. The segments are linked with bolts in a lining ring. The joints between concrete segments are weak parts in burdening soil and water pressure. So, to investigate the influence of joint mechanical characteristics on internal force distribution is very important for design of concrete segment section. Cao analyzed tunnel lining structures using multi-scale modeling method [1]. Arnau performed three-dimensional structural response of segmental tunnel linings [2]. Chen simulated crack problems in segments of shield tunnel using finite element method [3]. Do investigated segmental tunnel lining behavior using numerical method [4]. Tan studied engineering geological conditions and railway tunnel scheme across Qiongzhou strait [5]. Taking Qiongzhou Strait Submarine Tunnel as an example, this paper studies the internal force distribution characteristics of concrete segments under two loading conditions.

Taking underwater tunnel in Qiongzhou strait as an example, the two soil and water pressure loading models are proposed to investigate influence of segment joint mechanical characteristics on internal force distributions on concrete segments. Qiongzhou strait is located in between Leizhou...
peninsula and Hainan island, China. The minimum straight distance is 18km. The out-diameter of
designed undersea tunnel is 11.1m. The height of concrete segments is 0.6m. The deposited depth of
tunnel in soil layers is 50m, and depth of water is 80m. The concrete strength grade is C60. The elastic
modulus of concrete is 40GPa. The Poisson’s ratio of concrete is 0.2. The elastic modulus of soil
layers is chosen as 40MPa. The Poisson’s ratio of soil layers is chosen as 0.4. Two soil and water
pressure loading models are considered to investigate internal force distribution characteristics on
concrete segments. The first soil and water pressure loading model is called as combined calculation
model of soil and water pressure. In this loading model, the soil and water pressure acting concrete
segments is assumed that soil and water pressure is mixed together, the density of soil layer is
saturated density. In the first soil and water pressure loading model, it is assumed that the water in soil
layers is not free gravity water, and water will be constrained by soil skeleton and cannot flow in soil
skeleton. So, soil and water including in soil skeleton is regarded as indivisible whole. This pressure
loading model is applicable for poor permeability clay.

The second soil and water pressure loading model is called as separately calculation model of soil
and water pressure. In this loading model, the soil and water pressures acting concrete segments are
assumed to independently act on concrete segments. The density of soil layer is buoyant density. The
water pressure loading for both loading models acts on normal direction of concrete segment surfaces.
In the second soil and water pressure loading model, it is assumed that the water in soil layers is free
gravity water, and water can freely flow through soil skeleton. This pressure loading model is
applicable for sandy and silt soils. In the sandy and silt soils, there are more pores and poor cohesion
between granules.

As shown in figure 1, one lining ring of concrete segments consists of 9 segments and 9 joints. The
two segments are connected by 2 bolts in transverse section direction of tunnel. The segments are
simplified as beam element (BEAM3) in ANSYS software. The soil layers are simulated by PLANE42
element. The relations between concrete segments and soils are simulated by contacting elements.

2. Unchangeable stiffness beam model for concrete segment ring
To ignore the influence of joints on stiffness of segment linings, the concrete segment lining is
simplified as homogenous circle ring with unchangeable stiffness beam. The bending moment
distributions on concrete segment beam for two soil and water loading models are shown in figure 2. It
can be observed from figure 4 that the maximum bending moment on concrete segment for combined
calculation model of soil and water pressure is greater 2.28 times than separately calculation model of
soil and water pressure. The maximum positive bending moments for two soil and water pressure
computing models are located on roof and floor of concrete segment lining. The maximum negative
bending moments for two soil and water pressure computing models are located on strait wall of
concrete segment lining. The maximum negative bending moment is equal to maximum positive
bending moment in absolute value.
It can be observed from figure 3 that the maximum axial force on concrete segment for combined calculation model of soil and water pressure is greater 1.15 times than separately calculation model of soil and water pressure. The shapes of axial force on concrete segment for two soil and water pressure computing models are same. The maximum axial forces for two soil and water pressure computing models are located on straight wall of concrete segment lining.

3. Beams with hinges model for concrete segment ring
To ignore the bending resistance of joints on concrete segment linings, the joints of concrete segment lining are simplified as hinge joints without burdening bending moments.
It can be observed from figure 4 that the maximum bending moment on concrete segment for combined calculation model of soil and water pressure is greater 2.89 times than separately calculation model of soil and water pressure.

It can be observed from figure 5 that the maximum axial force on concrete segment for combined calculation model of soil and water pressure is greater 11.4% times than separately calculation model of soil and water pressure.

4. Beams with rotating stiffness spring model for concrete segment ring

In fact, the homogenous circle ring model with unchangeable stiffness beam overvalues bending resistance of joints, and hinged model ignores bending resistance of joints. So, the reasonable computing model for simulating joints of concrete segments is to take joints of concrete segments as rotating springs with rotating stiffness. Based on the section size of tunnel and connecting bolt property and experimental data [6], the rotating stiffness of rotating springs is determined as $k_\theta=70000\text{kN} \cdot \text{m/rad}$. 
It can be observed from figure 6 that the maximum bending moment on concrete segments for combined calculation model of soil and water pressure is greater 2.5 times than separately calculation model of soil and water pressure.

It can be observed from figure 7 that the maximum axial force on concrete segments for combined calculation model of soil and water pressure is greater 13.7% times than separately calculation model of soil and water pressure.

5. Discussion
From the above results, it can be seen that under the two loading conditions, there is no difference in the internal force distribution style in the segments, but there is a significant difference in the numerical value. It can be seen that under different soil conditions, the loads formed by the combination of soil and water are different, which has important reference value for construction design.

6. Conclusions
Shape of bending moments on concrete segments are basically same for combined model of soil and water pressure and separately model of soil and water pressure. The maximum bending moments on concrete segments for combined model of soil and water pressure are greater 2.28, 2.89 and 2.5 times than for separately model of soil and water pressure when using unchangeable stiffness model, range model and rotating spring model for concrete segment joints.
The axial forces on concrete segments are compressive states for both combined model of soil and water pressure and separately model of soil and water pressure. The maximum axial forces on concrete segments for combined model of soil and water pressure are greater 15.5%, 11.3% and 13.7% times than for separately model of soil and water pressure when using unchangeable stiffness model, range model and rotating spring model for concrete segment joints.

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