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Large scale three-dimensional seepage analysis model test and numerical simulation research on undersea tunnel

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ABSTRACT

During the construction process of Qingdao Jiaozhou Bay Undersea Tunnel, the faults and other unfavorable geological discontinuities were often encountered. To study the water inrush mechanism in the faults, both physical model test and numerical analysis were carried out. The results of crown displacement and hydraulic pressure of the monitoring sections in the physical model and numerical model were analyzed in this paper. It was found that the displacement and hydraulic pressure in the process of tunnel construction are often interacted as both cause and effect, and the lower of hydraulic pressure is often accompanied with the growth of its displacement. The changing of the excavation disturbed zone during the excavation in the undersea tunnel was also studied. The results show that the excavation disturbed zone in fault is larger than that in surrounding rock mass, and the excavation disturbance effects in the filling type fault are both transient and persistent. When the displacement and hydraulic pressure in the undersea tunnel change sharply during excavation, there are relatively slow and continuous change trend of the displacement and hydraulic pressure. For practical purposes, to prevent water inrush in the undersea tunnel, more attentions should also be paid to the undersea tunnel after excavation.

1. Introduction

Undersea tunnel is the preferred means of cross-sea traffic in China. However, the construction of undersea tunnel is often hindered by several challenges including high hydraulic pressure and fragile geological conditions. During the construction process of Qingdao Jiaozhou Bay Undersea Tunnel, about 18 faults were encountered. Due to the low strength, low stiffness and large porosity of the faults, the stability of the faults should be studied before the excavation of undersea tunnel.

Physical model test is one of the most effective means to investigate the rock mass response due to the underground excavation. Sun et al. [1] conducted a model test of the portals of two parallel tunnels to capture the dynamic response of tunnel liner and the interaction between surrounding rock mass and liner in earthquakes. Li et al. [2] carried a 3-D physical model to clarify the effect of the dipping formation and bidirectional excavation on the tunnel deformation. Li et al. [3] explored a new physical model based on the digital speckle correlation method (DSCM) to investigate the deformation and failure modes of weak rock mass surrounding a tunnel. Jeon et al. (2004) performed a scaled model test to observe the effect of faults, weak planes, and grouting on the stability of a tunnel. Geomechanical model tests were also conducted by Lin et al. [9] to investigate the failure behavior and instability of the tunnels constructed in the Jinping II hydropower station. However, the above-mentioned physical model tests can not analyze the seepage problem well because of the higher requirements of the model frame, the analogous material and the testing method for seepage model test.

The numerical analyses for the seepage problem have also been carried out. In the existing numerical analyses, continuum-based [5,6] and discontinuum-based methods [7,8] are two major approaches employed to analyze the rock mass response due to the underground excavation. Lee and Nam [11] analyzed the distribution of the seepage field and the seepage force during the process of excavation of shallow tunnel and underwater tunnel with circular section. Yao et al. [12] proposed a seepage analysis model for karst collapse columns and imported into COMSOL to analyze the water inflow evolution. Some researchers have also carried out a series of numerical calculations to study the characteristic of fault rupture zone using the theory of seepage analysis. Ma et al. [13] used the

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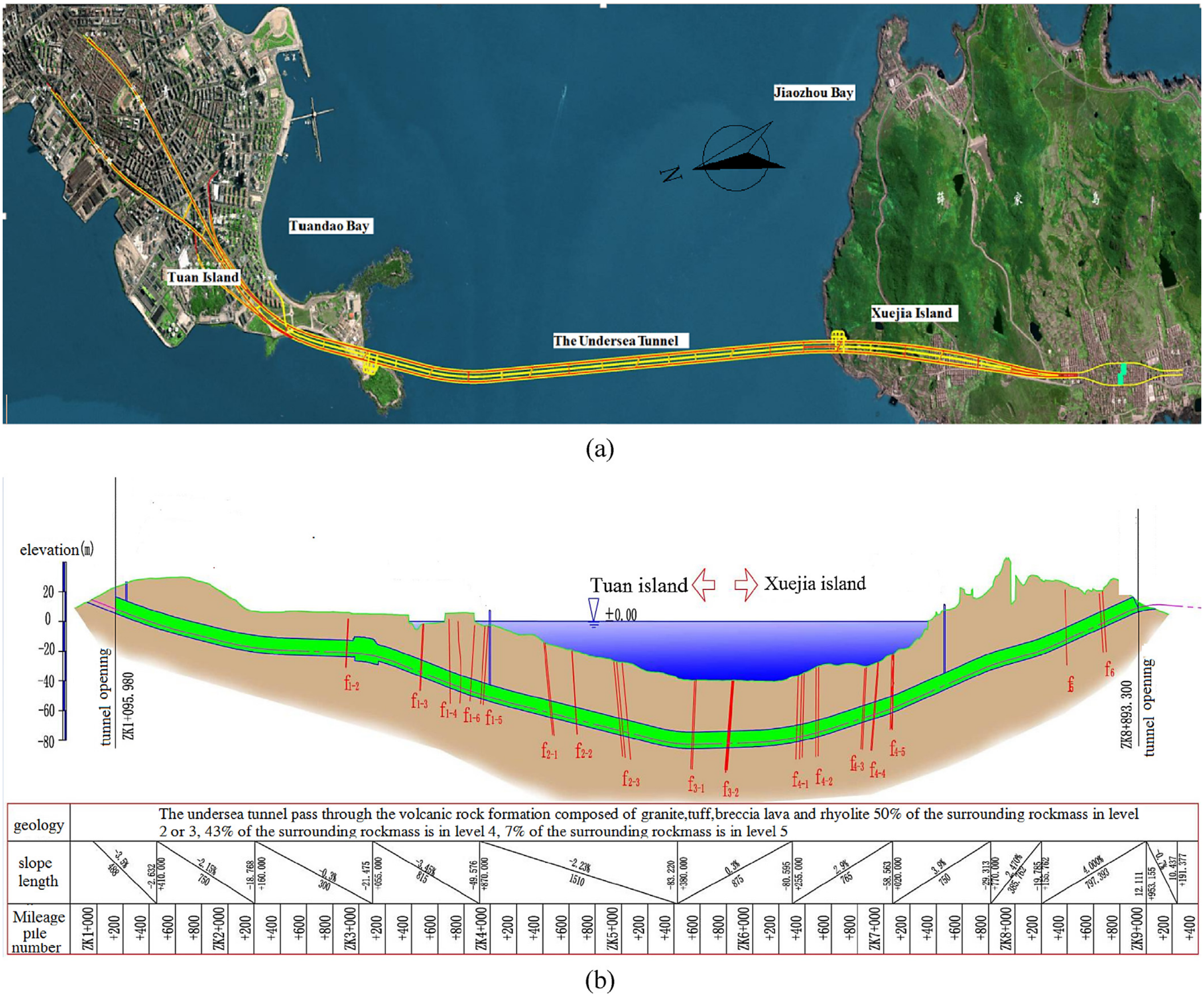

Fig. 1. Geographical position of Qingdao Jiaozhou Bay Undersea Tunnel.

fluid-mechanics system of 3-Dimensional Distinct Element Code (3DEC) to solve the problem of water loss during mining of shallow, buried coal seams. To simulate the hydraulic–mechanical interaction in the process of cracking, Bian et al. [14] proposed a coupling method based on the three-dimension elastic-plastic finite element method (FEM). Nan et al. [15] established an optimized mining model through seepage-stress coupling orthogonal experiment to investigate the feasibility of backfill mining method and the optimal parameters of mining design. Chen et al. [16] proposed a coupling analysis model to study the hydro-mechanical response of the fluid flow in fractured rock mass with the method of discontinuous deformation analysis (DDA). Yang et al. [17] described a seepage–stress cross-coupling anisotropic model considering the coupled effect of the seepage and stress. The reinforcement design and stability analysis for large-span tailrace bifurcated tunnels was also done by Lin et al. [18]. Most of the previous studies were suitable for the analysis of the mining engineering or mountain tunnels, there is a need to analyze the stability of the fault in the undersea tunnel using the theory of seepage analysis.

In this paper, the process of water inrush was analyzed by using a self-developed large-scale physical model test and a numerical simulation with FLAC3D Software. The variations of the displacement and the pore water pressure during the process of water inrush were also analyzed. The results could finally serve as references for construction design and disaster warning of water inrush in the undersea tunnel.

2. Engineering background

Qingdao Jiaozhou Bay Undersea Tunnel is the second undersea tunnel in China located between the major city and assistant city of Qingdao with total length of 7120 m (see Fig. 1). The south and the north of the tunnel connect with the Xuejia Island and the Tuan Island, respectively. The average depth of water is about 30 m. The tunnel was excavated using the mining method and supported by composite lining. The height and width of the tunnel were designed as 11.2 m to 12.0 m and 15.23 m to 16.03 m, respectively.

In the process of construction, the tunnel passed through 18 large regional faults (signed as $f_{1\text{-}1}$ to f_6) including 6 faults in Tuan Island, 10 faults in the sea, and 2 faults in Xuejia Island (see Fig. 1). Most of the faults were mainly composed of cataclasite and mylonite. The section of YK6 + 920–YK6 + 956 (the section was located between 6.920 km and 6.956 km) in the tunnel right line with a length of 36 m developed the fault named