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Stability Evaluation of Concrete Structure Considering the Local Damage Using Nondestructive Detection and Numerical Analysis

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Abstract. Shield tunneling is one of the most important technologies for building of underground engineering. Many grouting holes were prefabricated for the requirement of backfill grouting, which is easy to induce local damages and potential disasters, such as leakage and cracking. Accordingly, an integrated workflow for damage detection and stability evaluation was performed based on nondestructive testing (NDT) and numerical simulation. As a case study, this method was applied to an underwater shield tunnel. Firstly, Ground Penetrating Radar (GPR) was used to detect the conditions in grouting holes. Then, the infrared camera was used to determine the damaged positions induced by grouting holes. According to NDT results, the numerical models were developed to analyze the mechanical behaviors of structure. It indicated the geophysical inversion results are consistent with field conditions. The influence area increases with a significant value of water pressure, and stress magnitude would increase to 45KPa if the increment of water pressure reaches to 10KPa. As a promising application, structure stability was evaluated in the light of analytical results.

Keywords: Stability, Mechanical behaviors, Nondestructive testing, Numerical analysis.

1. Introduction

Maintaining the stability of infrastructure is crucial to the development of national economy. In the past few years, a mass number of researches are focused on the instability prevention of structure [1]. Especially for the shield tunnel, it is easier to suffer abnormal conditions because the complex structure and the existing of segment joints, such as leakage [2]. Many grouting holes were prefabricated in shield tunnels, and they were blocked off with special plugs and aged with time. The stress concentration occurred around the holes subsequently and it is easy to lead to local damage. In contrast to the previous studies, there are limited works about the detection of grouting holes and the investigation of local instability on the overall stability for an underground structure [3]. Based on the state-of-art for tunnel disasters prevention, the presented study focused on the development of an integrated workflow for local damages detection and its impact on structural stability using nondestructive testing (NDT) and numerical simulation.

An integrated workflow includes at least three components, reliable testing, reasonable analysis, and



effective measures. The field detection of tunnel conditions provides useful information to analyze the future mechanical behaviors of structure. During the past decades, various techniques and methods have been presented to detect the damaged conditions of tunnel structures [4]. However, these methods focus on local leakages induced by lining crack and openings between tunnel segment joints [5]. There are limited works on the testing of grouting holes. Considering the field geological condition and environment are complicated, the nondestructive testing (NDT) is a reliable method to inverse the internal conditions of objects in a non-damaged way [6,7]. This method has been widely used in underground constructions to detect the conditions of surrounding rock, geological structures, and the cavity thicknesses behind the tunnel lining [8,9]. It provides valuable references for maintaining the stability of civil structures. Also, numerical simulation is one of the most critical components for the integrated framework. In recent years, many numerical models have been used to analyze the mechanical behaviors of structure, such as discrete element method (DEM), finite element method (FEM), and the coupling of them [3,5,10]. Numerical modeling in the light of field results considering real geological conditions for the study site is critical to ensure the stability for civil structure [11]. In this study, a finite element model was developed to analyze the influence of local damage on the structural stability. As a case study, the presented method was employed in an underwater shield tunnel. The mechanical behaviors under different boundary conditions were also discussed. As a promising application, structure stability was evaluated in the light of analytical results.

2. Characterization of Underground Structure in the Study Site

The Nanjing Yangtze River tunnel, an underwater shield tunnel, is located at Nanjing, Jiangsu, China. Its coordinate is N32°04'1.12", E118°43'27.39". The field investigation indicates that the main geological layers passed by tunnel are silty-fine sand, clay, silty clay, medium-coarse sand, weathered siltstone, and pebbles, as shown in figure 1, and there is no visible fracture structure.

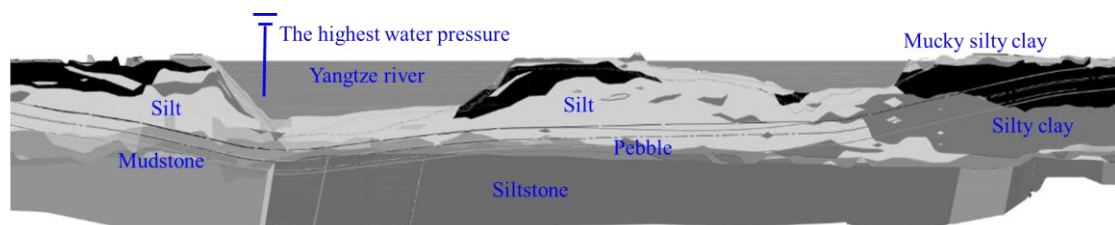


Figure 1. The geological profile of Nanjing Yangtze River tunnel.

The total length of the underwater shield tunnel is 7.014km. The external diameter of the tunnel is 14.5m, and the ring width and thickness are 2.0m and 0.6m, respectively. The segment is the main supporting structure, and no second-lining was applied for this underwater shield tunnel. To fill the interspace between segments and surrounding rock, backfill grouting technology is carried out after segment assembling. A grouting hole was prefabricated in the center of each segment. In order to prevent disasters of structure, some water pressure sensors and concrete stress sensors are installed in segments. As an example, the monitoring results of some points from July 30 2018 to July 30 2019 were displayed in Figure 2, which are obtained from the sensors monitoring results in field. This figure shows that the variation trend of concrete stress and water pressure are consistent, and both of them varied with seasons significantly.

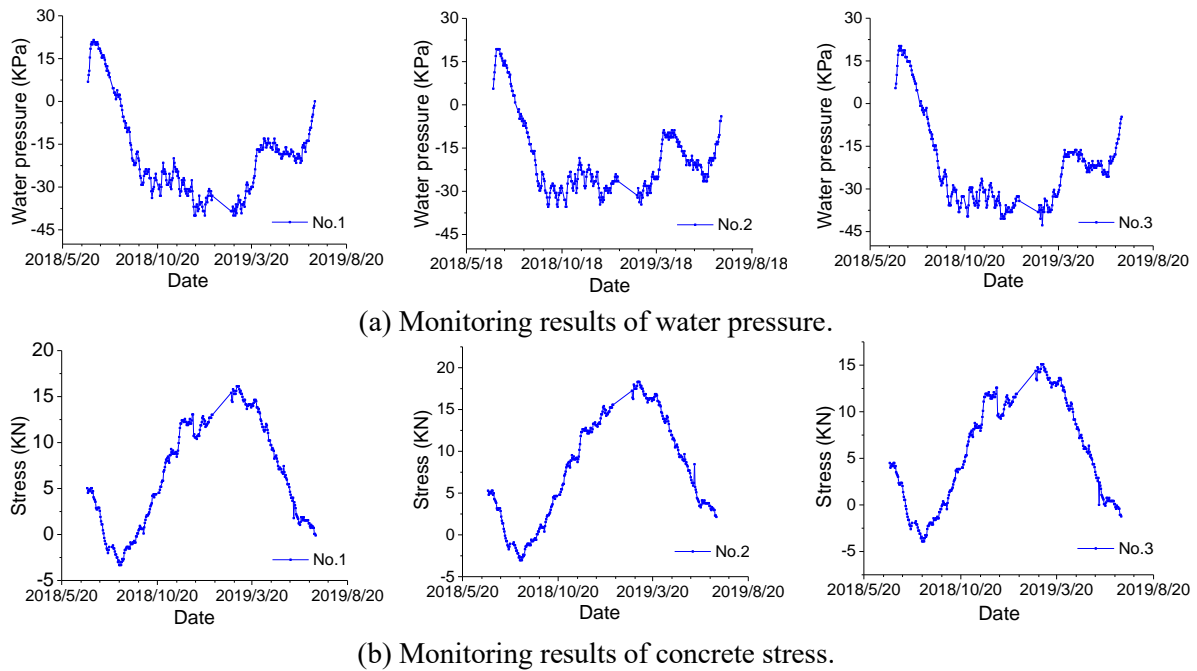


Figure 2. Field monitoring results.

3. Framework of Local Damage Assessment for Concrete Structure

3.1. The Proposed Workflow for Structure Stability Evaluation

Based on the research statues and the background of the Nanjing Yangtze River, this study developed a framework for the local damage assessment of structure. The workflow of the proposed methodology is displayed in figure 3. As shown in this figure, the presented workflow mainly involves two parts, field investigation and numerical analysis, where numerical modeling is based on the field investigation results.

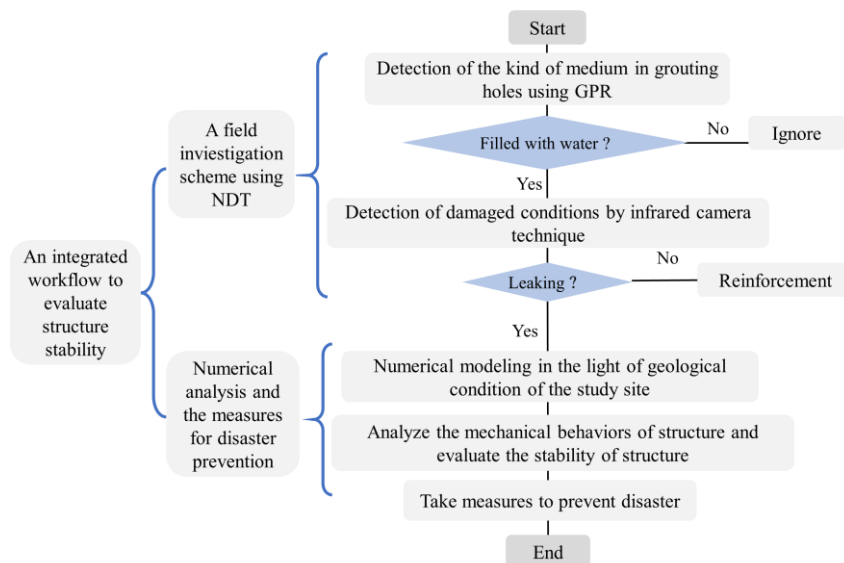


Figure 3. The workflow of the proposed methodology.

3.2. Detection Method for the Local Damage

Field detection provides an effective approach to prevent tunnel disasters. Considering the surface of tunnel lining is covered by fire-proof plates, the NDT method is a reliable method to detect the internal condition of an object through physical properties and it cannot affect the performance of structure.^{6,7} It is a new attempt to detect the conditions of grouting holes using NDT method. In this study, the local damage induced by grouting holes is regarded as the standard to judge damaged locations. Firstly, the Ground Penetrating Radar (GPR) was applied for geophysical inversion of the mediums in grouting holes, which could be divided into three categories, empty, filled with water, and filled with grout. If the grouting holes are empty, they are regarded as safe, and it is unnecessary to further detection and analysis. On the contrary, the infrared camera is used to determine the damaged locations by judging if water is leaking. Compared with the traditional application, it is a novel practice to detect the conditions of grouting holes by combing GPR with thermal infrared camera, which provides necessary information to maintain the stability of structure.

3.3. Numerical Modeling

Numerical modeling in the light of geological conditions of the study site is vitally important for structural stability evaluation. In this study, the beam-spring model presented firstly by Koizumi and Murakami is carried out for modelling [12]. The tunnel lining is considered as a beam model, and nonlinear springs are arranged around the external surface of lining to represent the influence of ground resistance. The stress boundary conditions are introduced to the improved model. The water pressure for an individual section is calculated as

$$P_i^w = \gamma_w h_i \quad (1)$$

where γ_w and h_i are the unit weight of water and water level of section I, respectively. The overlying soil pressure P_i^{up} , foundation soil pressure P_i^{bot} and side soil pressure P_i^{side} can be represented as

$$\begin{cases} P_i^{up} = \sum_{j=1}^n h_j (\gamma_j^s - \gamma_w) \\ P_i^{bot} = P_i^{up} + \frac{G - F}{d} \\ P_i^{side} = \sum_{j=1}^n \left(h_j + \frac{d}{2} - y \right) (\gamma_j^s - \gamma_w) \lambda_j \end{cases} \quad (2)$$

where n is the number of geological layers. γ_j^s is the unit weight, and h_j is the thickness of geological layer j . d denotes the external diameter of the tunnel. λ_j denotes the horizontal pressure coefficient. G and F are the gravity and buoyancy of the tunnel, respectively.

4. Identification of local damages in site using NDT

Following the workflow displayed in figure 3, the NDT method was applied to the Nanjing Yangtze River tunnel to detect local damage.

4.1. Detection Results of GPR

The antenna was placed on the positions of grouting holes, and three different patterns of geophysical inversion results are obtained, as figure 4 shown. They denote that electromagnetic wave is malposed for the influence of grouting medium. The wave phase has a trend to bulge upward, but the trend decreases with the rise of detection depth. Also, the intensity and range of abnormal signal varied with the different mediums, and the intensity of detection signal in the empty hole is most significant among all filling mediums. The detection depth of electromagnetic wave is over 50cm in an empty hole. The

signal in the grout hole is smooth, and the detection depth is less than 25cm. The intensity and range of the reflected signal in water are in between the other mediums, and the detection depth in this medium is about 40cm. Compared to empty holes, it is difficult to recognize the boundary between holes and surrounding medium at the bottom of holes in water and grout.

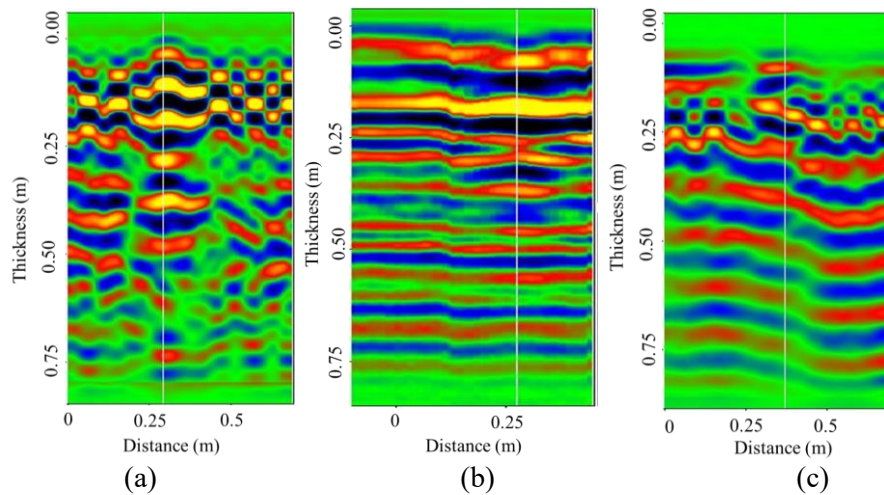


Figure 4. The different conditions of grouting holes obtained from field detection: (a) empty, (b) filled with water and (c) filled with grout.

4.2. Detection Results of Infrared Camera

Based on the detected results of GPR, the infrared camera is used to detect the conditions of holes filled with water and grout. As an example, the detection results and field condition is shown in figure 5. This figure shows the boundaries of damaged range in infrared thermography is clear, and the temperature at these positions are lower than others. To verify the reliability of detected results, some holes were selected for manual testing. The verified result is shown in figure 5c, which denotes that the inversion results are reasonable.

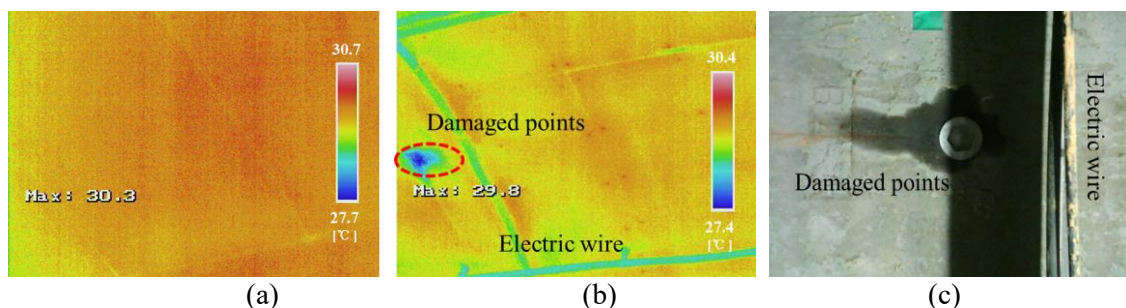


Figure 5. The field detection results of thermal infrared camera: (a) the safety condition, (b) the leaking condition and (c) a leaking grouting hole in field.

5. Numerical Modeling Based on the Results of NDT

5.1. Model Setup

The field investigation results denote that the water pressure applied to this position is about 427KPa, and the geological conditions are shown in figure 6a. As an example, a typical damaged position, located in the arch crown of tunnel, is selected for mechanical analysis. The length of the numerical model is 50m, and the damaged position is located in the middle of this model. The mechanical parameters used for modeling is displayed in table 1. Thus, the numerical model of the study site is shown in figure 6b.

Table 1. Mechanical parameters of surrounding grounds for the study site.

Ground types	Horizontal pressure coefficient	Ground resistance (MPa/m)	Unit weight (KN/m ³)
Silt	0.43	5	19.4
Fine sand-1	0.40	50	19.3
Fine sand-3	0.37	35	20.2
Silt clay	0.65	12	18.6
Gravel	0.25	80	20.6

5.2. Numerical Results under Different Boundary Conditions

The water pressure applied on tunnel varied with seasons in the service period. To analyze the influence of local damage under different water pressure, the water pressure applied to the numerical model are 427KPa, 457KPa, and 487KPa, respectively. The numerical results of different water pressure are shown in figure 7 where *C* represents the direction of circumference, and *L* represents longitudinal direction. The stress curves obtained from the numerical results are displayed in figure 8. It could be found that local damage increases stress in longitudinally, but decreases stress in circumferentially. The distribution of stress is symmetrical, and the stress in longitudinally is larger than that in circumferentially. In addition, the influence of local damage decreases with the increasing of distance from grouting hole. The largest stress is located in longitudinal direction, and it would increase with the increasing of water pressure. Based on the numerical results, it could be calculated that stress would increase 45KPa when the water pressure increases 10KPa.

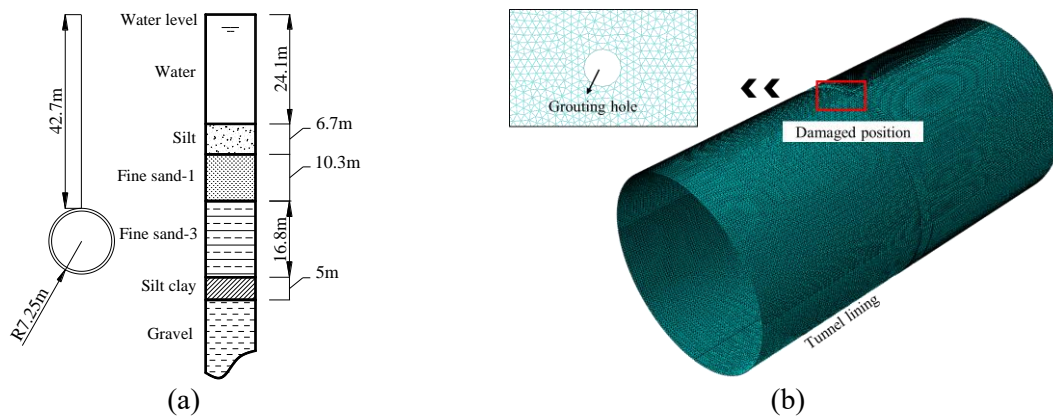


Figure 6. Numerical modeling for the study site: (a) geological conditions and (b) numerical model.

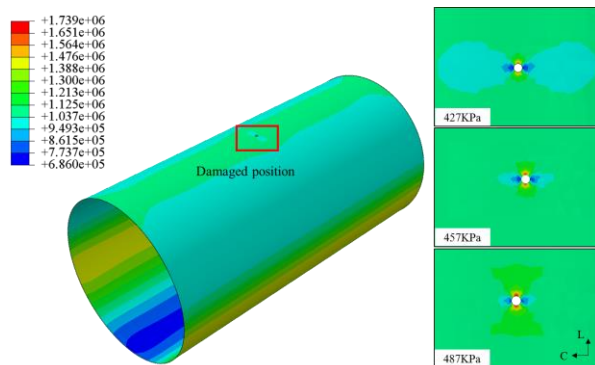


Figure 7. The influence of local damage under various water pressures.

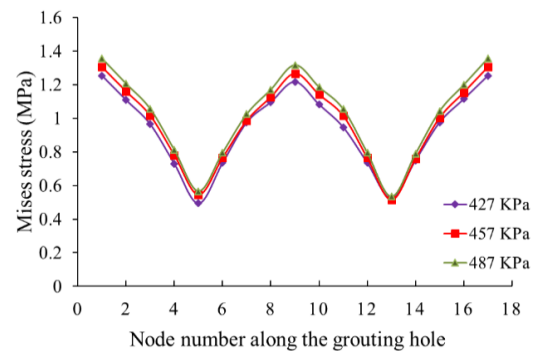


Figure 8. Mises stress along the grouting holes under different water pressure.

5.3. Application: Assessment of Structure Stability

The numerical results indicate that the damage of grouting hole increases the local stress of concrete lining. Thus, this section focuses on the assessment of structure stability and disasters prevention.

The tensile stress is reached to 1.74MPa under a water pressure of 487KPa, and the tensile stress would increase 45KPa if the water pressure increases 10KPa. The field investigation results denote the variation of water pressure applied to the study site is about 70KPa (compared to 427KPa). Accordingly, it could be calculated the largest tensile stress is about 1.79MPa. To evaluate the stability of the structure, the maximum tensile stress theory was considered as the criterion of crack propagation for concrete lining [13], as expressed

$$K \leq \sigma_u / \sigma_t \quad (3)$$

where σ_u is stress magnitude of concrete lining, and the value of concrete (C60) is 2.85 MPa. σ_t is the tensile stress around grouting hole. K is the safety factor [14]. According to equation (3), it can be calculated that the value of safety factor is 1.59 for this project, which is larger than 1.5 and the structure is safe [14].

6. Conclusions

In this study, an integrated framework was proposed to detect damage conditions and evaluate structural stability using NDT and numerical investigation. As a case study, this method was used to a typical underwater shield tunnel. The main conclusions are summarized as follows.

(1) The workflow of the integrated framework was performed in this study, which consists of physical model experiment, field detection using NDT, and numerical simulation. As a promising application, structure stability was evaluated in the light of its geological conditions.

(2) The NDT method was used to detect the conditions of grouting holes and determine the damaged positions. Based on the calibrated results, the GPR and infrared camera were used to geological field inversion. It has been proved that the inversion results agree well with the field data.

(3) The numerical model was used to analyze the effect of local damages on the stability of tunnel structure. The distribution of stress distribution was studied under various water pressures. The analytical results implies a considerable water pressure would induce increased value of stress. Stress magnitude would increase to 45KPa when the increment of water pressure reaches to 10KPa.

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