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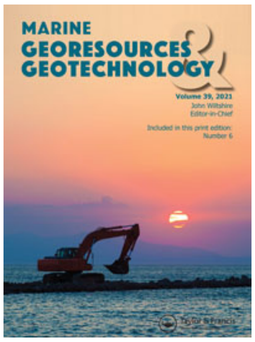

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Settlement behaviors investigation for underwater tunnel considering the impacts of fractured medium and water pressure

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ABSTRACT
Settlement behavior plays an important role for the stability of underwater tunnel due to the different responses of fractured surrounding rock to external load. In contrast to the traditional analysis method based on continuum mechanics, the presented numerical model using improved hybrid finite element was performed to study the settlement behaviors of structure, and structural health monitoring system (SHMS) was introduced for field verification. The Nanjing Yangtze River tunnel, a typical underwater shield tunnel was selected as a case study for numerical simulation and real-time monitoring. First, an improved numerical model was developed on the basic of our previous research, which considers the impact of natural geological fractures on structure stability. Then, numerical investigation was applied to study the displacement of settlement under different boundary conditions. The differences between intact and fractured surrounding rock were discussed, which denote the response of fractured surrounding rock is significantly larger. To verify the numerical results, SHMS was employed in this project to monitor its mechanical behaviors. On the basis of the mass monitoring data, the analytical method was introduced to investigate the response of tunnel settlement to water pressure, which agreed well with the results obtained from the model of fractured surrounding rock.

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KEYWORDS
Underwater tunnel; fractured rock; numerical simulation; real-time monitoring; settlement

1. Introduction

With the development of infrastructure system in urban areas, many shield tunnels have been constructed in recent years. The settlement behaviors caused by shield tunneling were hard to avoid, especially in soft and sandy stratum. In the period of underground construction, the excavation, shearing, extrusion, and backfill grouting generated by tunnel boring machine (TBM) have serious impacts on the stability of surrounding rock, which are the main reasons to induce tunnel settlement (Cattoni et al. 2016). Particularly, the fractures are ubiquitous and randomly distributed in jointed rock (Wang, Chen, Tan, Tan, Yang, et al. 2020; Wang, Chen, Tan, Tan, Yuan, et al. 2019). The disturbance induced by tunnel boring machine lead to increasing of pore water pressure, which would decrease gradually but lead to consolidation of soil. The period of settlement is long, and it could last for three years and even more (Shirlaw 1995; Di et al. 2016). The settlement would lead to various structural disasters such as segment cracks, peeling-off and water leakage, which will threaten the safety of tunnel (Huang, Huang, and Zhang 2012). In the past years, several methods have been carried out to analyze the mechanical behaviors of tunnel settlement. Apart from experiments and field measurement, numerical modeling is also a reliable method to analyze the settlement behaviors in fractured surrounding rock (Kasper and Meschke 2006; Fu et al. 2016). However, it is still a challenge to simulate fractured medium in the field of computational mechanics. This study is focused on the analysis of tunnel settlement in fractured surrounding rock using the improved numerical model and real-time monitoring.

In order to investigate the stability of structures, many scholars have come up with analytical solutions. These methods could be divided into three categories, theoretical analysis, experiments, and numerical simulation. The traditional analytical solutions (Fu et al. 2016; Meng, Chen, and Kang 2018; Wang, Yao, et al. 2019) are mainly based on continuum mechanics and limit equilibrium methods (LEM). The geological layer is assumed as an untrained elastic medium in most theoretical analysis, which limits the settlement study longitudinally. The experimental modeling is a widely used method to analyze the settlement behaviors of tunnel (Maeda and Kushiyama 2005; Hu et al. 2019). For a large-scale model, for instance the real field structures, it is a challenge for laboratory test or in-situ test to investigate its mechanical characteristics. Furthermore, since the period of settlement is long, the development of experiment modeling is limited. Numerical simulation is a kind of efficient approach to overcome the shortcoming, which can also consider the impacts of geological fractures on the stability of civil structures. However, there are limited literature studies

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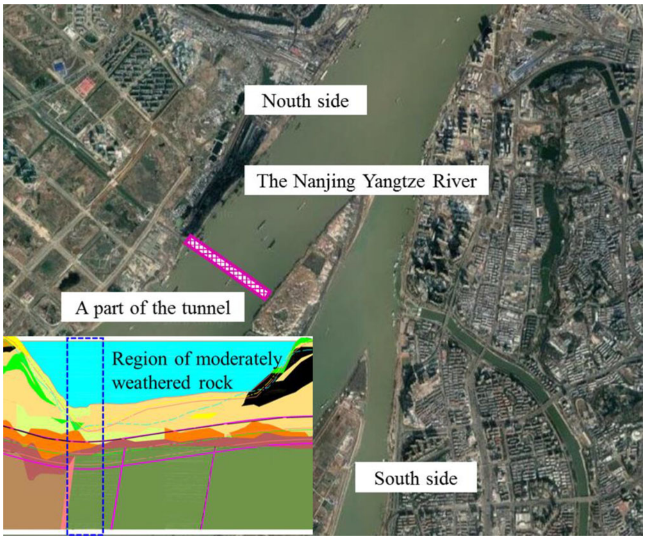


Figure 1. Location of the research area and its geological layer.

analyzing the impact of fractured rock on tunnel settlement. To this end, numerical simulation plays a unique role in settlement analysis because it could consider the impact of fractures and solve the difficulty of long experimental period (Migliazza, Chiorboli, and Giani 2009; Miliziano and Lillis 2019). The spatial structure of rock stratum has significant influence on settlement, and various numerical models have been setup to analyze the impact of fractured rock on structural stability (Yang, Liu, and Wang 2004). Among those various numerical models, discrete fracture network (DFN) is one of the most popular treatments to deal with stochastic fractures. The DFN was presented first by Long et al. (1982), and its properties varied with different scale levels. The typical models of DFN, such as Beacher disk model, orthogonal model, and Dershowitz model, have been employed to describe the fracture patterns of rock. In addition, the existing research has denoted that the DFN is widely used for geomechanical-hydrological work. But there are some difficulties related to this model, such as mesh generation problem and visualization problem (Wang et al. 2017; Karimi-Fard and Durlofsky 2016; Bisdom, Nick, and Bertotti 2017). In recent years, sensor monitoring has been applied in many infrastructural engineering projects, for instance, the Hong Kong-Macau-Zhuhai Bridge in china, and the monitoring results are reasonable. Compared with the traditional measurement technology, such as manual measurement, the new sensors achieved real-time and long-term monitoring. With the development of computer science, sensor monitoring was combined with center database to solve visualization problems. Sensor monitoring is a direct and reliable method to evaluate the feasibility of presented numerical model (Reynders, Wursten, and De. Roeck 2014; Jin et al. 2018).

In the light of geological conditions of a case study, the present study employed a numerical model to analyze the impact of fractured surrounding rock on tunnel settlement. The model was proposed based on the improved hybrid finite element method (FEM), which has been presented in our previous work (Wang, Chen, Tan, Tan, Yang, et al. 2020; Wang, Chen, Tan, Tan, Yuan, et al. 2019). Then the proposed model was verified using the real field monitoring data. First, the background and fracture patterns of the study case were introduced. Then, the stochastic fracture model of the study site was developed. The proposed model was discretized into different elements, and different mechanical properties were defined to these elements, respectively. In addition, the numerical results of tunnel settlement under different boundary conditions were discussed. Lastly, with the data collected from the structural health monitoring system installed in the field, the response of tunnel settlement to water pressure is analyzed, and by comparing the data with the simulated data, the presented numerical model is verified.

2. Characteristics of surrounding rock in the study site

To analyze the effect of fractured rock to the stability of tunnel, the Nanjing Yangtze River tunnel, located in typical moderately weathered rock and existing stochastic fractures, was selected as a study case for the presented investigation.

2.1. Study site

The Nanjing Yangtze River tunnel is a typical underwater engineering project with complicated geological conditions, located in Jiangsu province, China. It is one of the longest shield tunnels with complicated geological conditions in the world. The internal structure of this tunnel is also complex, which was designed as two-tubes and two-layers. The length of this project is about 7.014 km, and the external and internal diameters are 14.5 m and 13.6 m, respectively. The tunnel was built to connect the two sides of the Nanjing Yangtze River, and it is an important component for the nation city planning in research proposal.

According to the field geological investigation results, the layer at the mouth of Yangtze River is moderately weathered rock, as shown in Figure 1, which contains many fractures and they intersect each other. To investigate the influence of fractured surrounding rock to tunnel settlement, the region of tunnel in moderately weathered rock layer (Figure 1) was selected as the research area. During the service period, seasonal water pressure is applied to this tunnel. The water pressure would induce settlement and affect tunnel stability. In this paper, the research topic is to study the settlement behavior of the tunnel during its service period, with the effect of random fractures and various water pressure in consideration.

2.2. Fracture pattern of the surrounding rock

The field investigation results, shown in Figure 2, indicated that the geological conditions of surrounding rock for the Nanjing Yangtze River tunnel were complex. Many random fractures distributed in the inside of surrounding rock, and the existing fractures crossed each other. The fractures have great influence on the stability of structure and control structural mechanical behaviors. In order to describe the characteristics of fractured rock, many numerical models

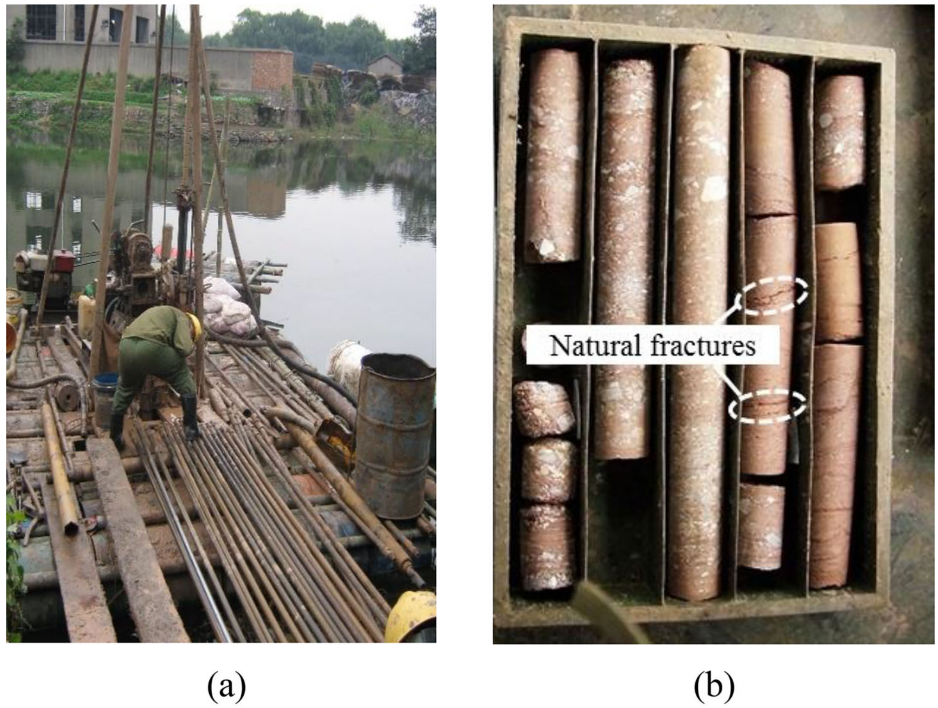


Figure 2. Geological exploration in the study site: (a) field environment and apparatus and (b) the rock samples obtained from the site.

have been presented in the past few years (Migliazza, Chiorboli, and Giani 2009). The type of fractured rock models could be summarized into three categories, as displayed in Figure 3. It was found that the traditional simulation of fracture distribution is in the framework of continuum mechanics and equivalent continuity hypothesis. The research domain is regarded as intact and continuous, and different reduction factors are introduced to represent the influence of fractures, as shown in Figure 3a. In recent years, some improved models considering the impacts of discontinuous surface and geological structures were presented, such as the discrete element model. The improved numerical model assumes that the fractures are distributed in parallel, as shown in Figure 3b. In this model, fracture inclines are predefined, and all fractures are generated according to the specified angles. It is not really a random distribution. These traditional models are oversimplified therefore they are relatively irrational. Compared with the traditional numerical models, the discrete fracture network (DFN) was carried out in this study to simulate the fractured surrounding rock, as shown in Figure 3c. The fractures are assumed to be randomly distributed in the research domain, and some of them crossed each other. It is an important improvement because this presented model considered the impact of random fractures and bedding planes. Thus, the improved model was used to describe the fracture pattern of Nanjing Yangtze river tunnel.

3. The stochastic fracture model and numerical treatment

As discussed in the above sections, the stochastic discrete fractures were generated on the basis of the fracture patterns of surrounding rock. In this new method, the influence of DFN on the mechanical behaviors of structure is considered by integrating them into finite element method (FEM). The numerical model of fractured surrounding rock was established. Then, the proposed model was discretized into different elements, and different mechanical properties were defined to these elements, respectively.

3.1. Generation of stochastic discrete fractures

The fractures created under a special geological condition mainly exist in a form of network, which makes the rock mass discontinuous and anisotropic. The distribution of stochastic fractures has been widely reported by many studies (Yang, Liu, and Wang 2004; Long et al. 1982), and many characteristic parameters were used to describe them, such as trace length, center coordination, and inclination angle. Based on our previous research, an improved hybrid finite element method was developed by our group to generate discrete fracture networks (Wang, Chen, Tan, Tan, Yang, et al. 2020; Wang, Chen, Tan, Tan, Yuan, et al. 2019). The DFNs model was used to construct the geometry of multiple fractures (Barton, Bandis, and Bakhtar 1985). The characteristics and parameters of stochastic discrete fractures were defined beforehand as follows.

(a) Definition of the trace length. In the light of field investigation results, some researchers have summarized that the distribution law of trace length corresponded to the logarithmic normal distribution (Lei, Latham, and Tsang 2017). Thus, for an individual fracture *i*, the common density function is represented as follows:

$$F(l_i) = \frac{1}{\sqrt{2\pi}} e^{\frac{-(\ln l - \mu)^2}{2\omega^2}} \tag{1}$$

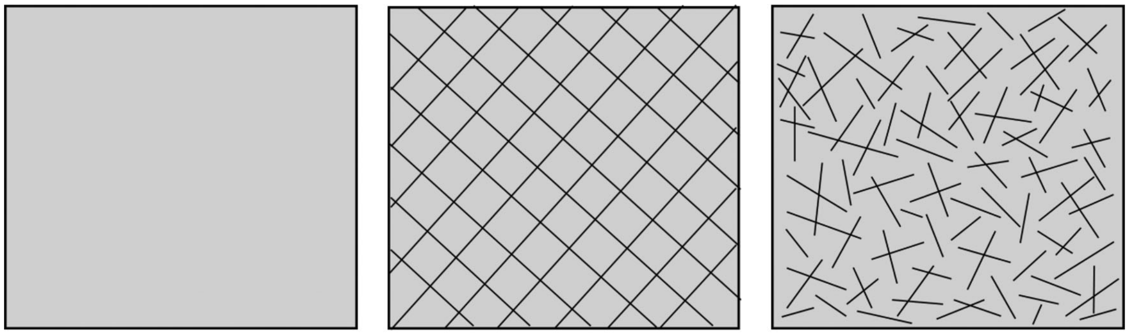


Figure 3. The typical conceptual model of different fracture patterns: (a) the original model, (b) the improved model, and (c) the presented random fractures model in this study.

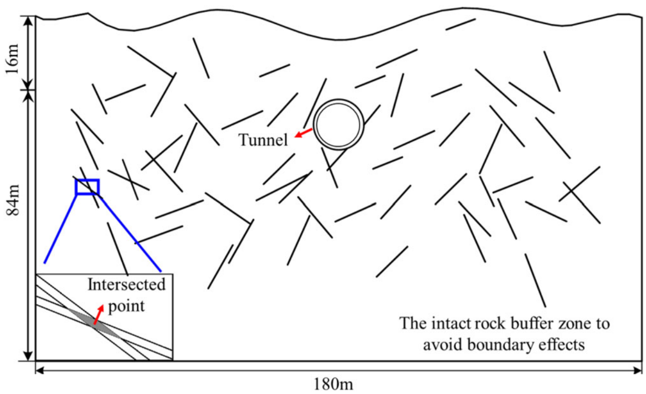


Figure 4. Numerical model of fractured surrounding rock in the Nanjing Yangtze River tunnel.

where l is the trace length of fracture i, ω and μ are the parameters of density function.

(b) Definition of the inclination angle. According to the geo-statistics, the parameter of inclination angle obeys normal distribution law, which has been reported in existing literature (Lei, Latham, and Tsang 2017). It could be calculated as follows:

$$I(\alpha_i) = \frac{1}{\sqrt{2\pi}\chi} e^{\frac{-(\alpha-\eta)^2}{2\chi^2}} \tag{2}$$

where α represents the inclination angle of fracture i, χ and η are the parameters of distribution function.

(c) Generation of the center points of fractures. The center point is vitally important to decide the endpoints of fracture. To determine the positions of fractures, the rock matrix was assumed to be portioned into multiple unit volumes. In general, the distribution of center points in per unit volumes follows a Poisson distribution law (Priest 1993). It was calculated as follows:

$$P(n) = \frac{\lambda^n}{n!} e^{-\lambda} \tag{3}$$

where n is the number of unit volumes, and λ is the number of fractures in every unit volume.

Based on the characteristic parameters of trace length, inclination angle, and center points, the algorithm for generating fractures was developed to create DFNs, which has been made a detailed introduction in the previous studies (Wang, Chen, Tan, Tan, Yang, et al. 2020; Wang, Chen, Tan, Tan, Yuan, et al. 2019). As an important application, the algorithm was applied to simulate the fractured rock surrounding in the Nanjing Yangtze River tunnel. The burial depth of tunnel in research area is 56 m, consisting a depth of overlying soil 16 m and a depth of water 40 m. Based on the field investigation results (Figure 2), the fracture pattern of this study case was created, as displayed in Figure 4. The fractures stochastically distributed in the surrounding rock, and some factures intersected each other. Meanwhile, the intact rock buffer zone was carried out to overcome boundary effects (Bisdom, Nick, and Bertotti 2017). Furthermore, to illustrate the influence of factures on structural settlement, the tunnel was built in the fractured layers.

3.2. Discretization of the proposed model

The generation of finite element grid is important for the discretization of fracture model. In the last few years, many methods have been applied to generate the mesh of DFNs, such as unstructured and elliptic grids method (Bosma et al. 2017). However, it is still difficult to generate high quality mesh for DFNs model due to the random partition of fractures. Furthermore, the width of fracture is thin compared with the rock matrix, which also makes it challenging for partition.

To overcome these difficulties, the algorithm to generate hybrid elements of DFNs model was also developed by our group, as introduced in the previous research (Wang, Chen, Tan, Tan, Yang, et al. 2020; Wang, Chen, Tan, Tan, Yuan, et al. 2019). To analyze the mechanical behaviors of the Nanjing Yangtze River tunnel, the rock matrix and discrete fractures were discretized into triangular elements and quadrilateral elements, respectively, as shown in Figure 5.

3.3. Mechanical behaviors of fractures and the matrix

In order to analyze the settlement behaviors of tunnel in fractured surrounding rock, different mechanical properties were defined in the rock matrix elements and fracture elements. Meanwhile, the traditional continuum mechanics was carried out to describe their constitutive relation.

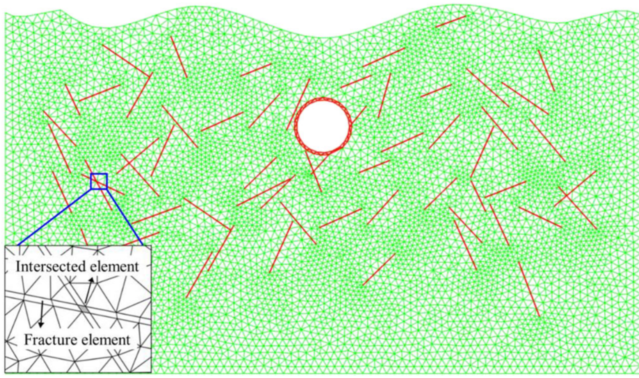


Figure 5. Generation of hybrid elements for the Nanjing Yangtze River tunnel.

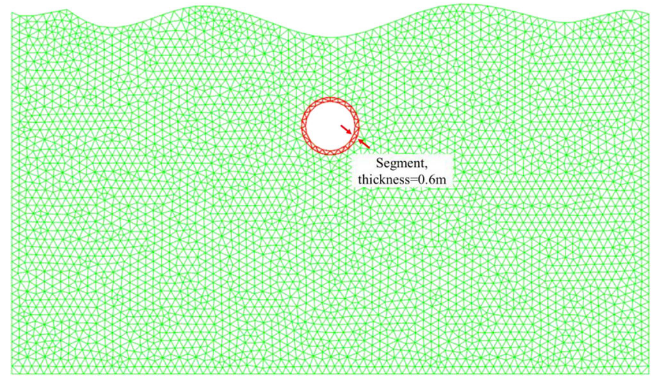


Figure 6. Numerical model for intact rock mass.

The cohesive elements were applied to simulate fractures and the coupling stiffness was ignored (Wang et al. 2017; Barton, Bandis, and Bakhtar 1985). Thus, when the normal and shear displacement are less than their critical values, the mechanical behaviors of fractures could be expressed as follows:

$$\begin{pmatrix} \sigma_n \\ \sigma_s \end{pmatrix} = \begin{pmatrix} K_{nn} & K_{ns} \\ K_{sn} & K_{ss} \end{pmatrix} \begin{pmatrix} \delta_n \\ \delta_s \end{pmatrix} \tag{4}$$

where δ_n, δ_s are normal and shear displacement, σ_n, σ_s are normal and shear stress corresponding with the displacement, respectively. K_{ij} $(i,j = n,s)$ is stiffness values of fractured element.

The fracture aperture would change under compressive condition. To describe this mechanical behavior, Bandis–Barton law (Barton, Bandis, and Bakhtar 1985) is introduced as follows:

$$\delta_n = \frac{\sigma_n b_f}{K_{in} b_f + \sigma_n} \tag{5}$$

where b_f is maximum fracture aperture and K_{in} is the initial stiffness.

Considering the effects of hydrostatic pressure, the Drucker–Prager (D–P) principle was carried out to define the mechanical response of rock matrix (Chen and Han 1988). For a two dimensional model, the yielding behaviors can be expressed as follows:

$$\sqrt{3}\beta(\sigma_1 + \sigma_2) + \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2} = \sqrt{3}k \tag{6}$$

where β and k are material parameters. They could be transformed by the parameters in Mohr–Coulomb model, as given in follows.

$$\beta = \frac{2\sin\varphi}{\sqrt{3}(3 + \sin\varphi)}, \quad k = \frac{6c \ \cos\varphi}{\sqrt{3}(3 + \sin\varphi)} \tag{7}$$

where c is cohesive strength, and φ is friction angle.

4. Results and discussion

In this section, a comparative model was developed to discuss the differences between fractured surrounding rock and intact rock model. In addition, based on the performed model, the numerical results were obtained to analyze the influence of water pressure on the tunnel settlement.

4.1. Model setup

As mentioned above, the Nanjing Yangtze River tunnel was selected as a case study to analyze the influence of fractured rock surrounding the tunnel settlement. The DFNs model of this project has been setup, as shown in Figure 5. In the field, the tunnel segments are the main supporting structure, which has vital importance on tunnel stability. The water pressure applied on the research area is variable during the service period, which is the main reason to induce settlement of structure because the responses of fractured surrounding rock to external load are different. To illustrate the influence of fractures on tunnel settlement, a contrast model, whose surrounding is intact rock was generated, as shown in Figure 6. Thus, the following is focused on the analysis of intact and fractured surrounding rock under different boundary conditions. According to the site investigation results, the mechanical parameters used for modeling of rock, fracture, and segment are displayed in Tables 1–3.

4.2. Numerical results of intact and fractured rock mass

The water pressure applied on the research area is about 0.4 MPa. The contour plot of tunnel settlement and the vertical displacement along the edge of tunnel segment were obtained from the established numerical model, as displayed in Figures 7 and 8. The Figure 7 shows the numerical results of fractured surrounding rock, which denotes that the vertical displacement of tunnel segment is continuous, however, the inflection points are obverted at the intersection of factures and tunnel segments. The smallest settlement is located in the hance of tunnel. Furthermore, the structure is upward in the position of arch bottom because the value of vertical displacement is negative. Above all, tunnel excavation has great influence on the settlement behavior of the overlying soil. The vertical displacement of arch crown is positive, which represents the position of tunnel settlement, and the influence of excavation attenuates with the increase of distance.

Compared with the fractured rock mass, the numerical results of tunnel settlement in intact surrounding rock were shown in Figure 8. It can be found that the vertical

Table 1. Mechanical parameters for rock.

Elastic modulus	Poisson's ratio	Frictional angle	Cohesive force	Density
10 GPa	0.21	42.2°	1.2 MPa	2630 kg/m^3

Table 2. Mechanical parameters for fracture.

Shear stiffness	Initial stiffness	Maximum fracture aperture	Density
5 GPa/m	0.45 GP/m	1.2 mm	2630 kg/m^3

Table 3. Mechanical parameters for tunnel segments.

Elastic modulus	Poisson's ratio	Density
36 GPa	0.2	2400 kg/m^3

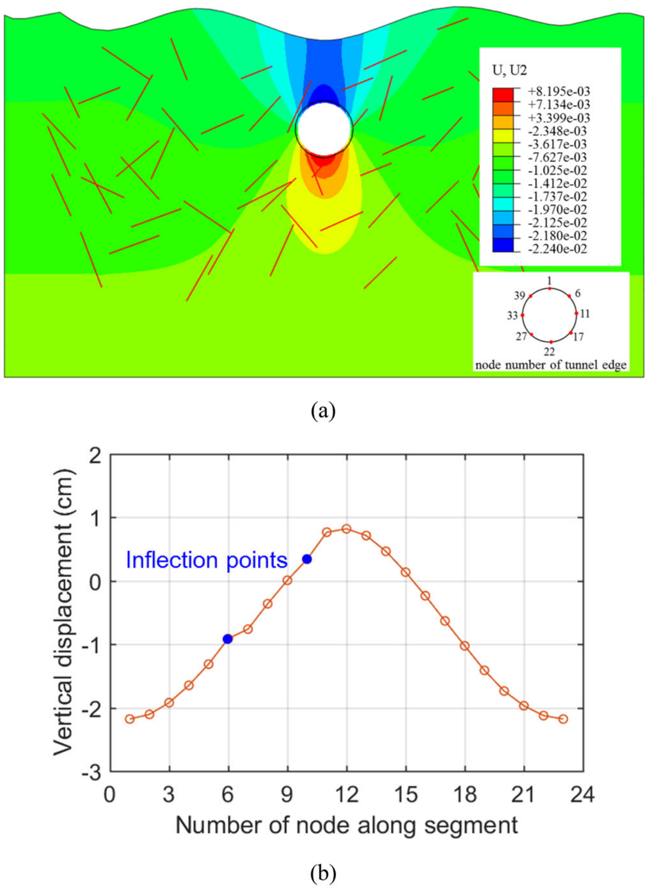


Figure 7. The numerical results of fractured surrounding rock: (a) displacement contour in vertical direction, and (b) vertical displacement along the edge of segment.

displacement of tunnel segment is continuous and there is no inflection point. The positions of largest settlement and smallest settlement are consistent between these two different rock masses. However, it is obvious that the magnitude of tunnel settlement in fractured surrounding rock is larger than that in intact rock mass. In addition, the influenced zone of tunnel settlement is different between these two conditions. The settlement occurred in fractured rock has greater influence on overlying rock mass. The revised contents have been highlighted in the manuscript, which indicated the importance of fractured surrounding rock for analyzing the response of tunnel settlement.

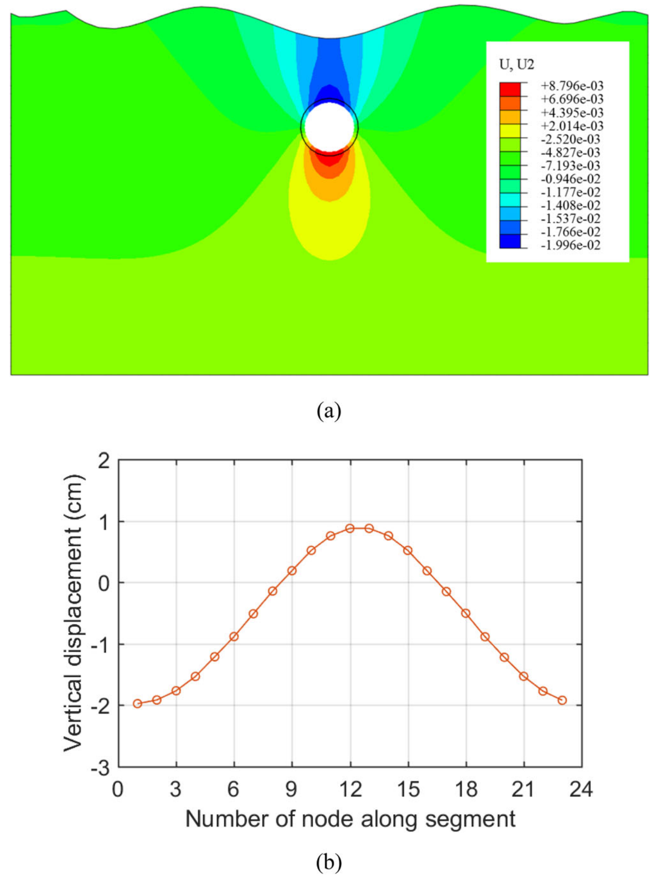
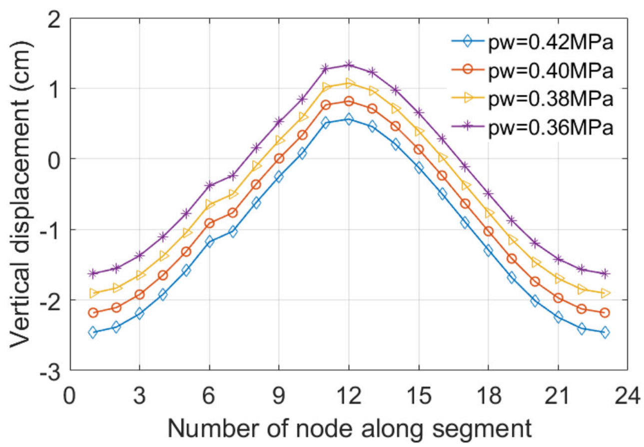


Figure 8. The numerical results of intact surrounding rock: (a) displacement contour in vertical direction, and (b) vertical displacement along the edge of segment.

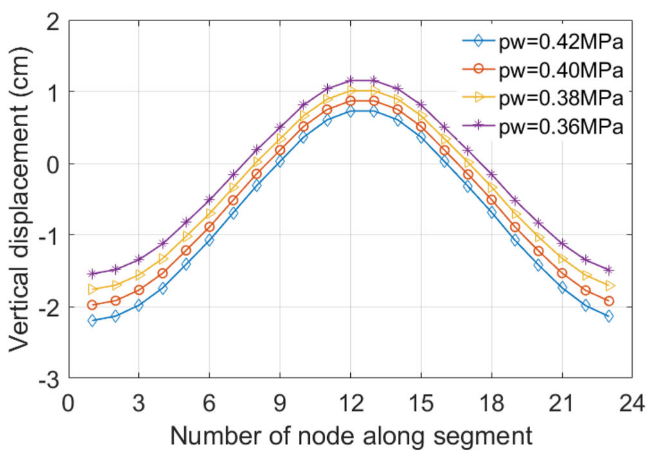
4.3. Effect of water pressure on settlement behaviors

As mentioned above, the field condition of underwater shield tunnel is complex, and many external loads applied on the structure. The water pressure is the main external load applied on tunnel, which would vary with seasons during the service period. To analyze the response of tunnel settlement to the variation of water pressure, different boundary conditions were applied on the presented numerical models. The water pressures loaded on the structure were 0.36 MPa, 0.38 MPa, 0.40 MPa, and 0.42 MPa, respectively.

Under the effects of different boundary conditions, the curves of vertical displacement along tunnel segment edge are shown in Figure 9. This figure indicates that the variation trend of vertical displacement is similar under different water pressures. The settlement of overlying soil on the arch crown of tunnel increases with the rise of water pressure. On the contrary, the upward behavior of arch bottom decreased with the rise of water pressure. It is well-known that the water pressure changes 10KPa if the water level changes 1 m. Thus, based on these results, the variation of tunnel settlement when the water level changed 1 m could be calculated as Figure 10 shows. It denoted that the response of arch crown is the largest, and that of arch bottom is the smallest. In addition, the magnitude of response to water pressure in fractured rock is larger than that in intact rock. It can be observed that the curve of settlement response is smooth in the intact surrounding rock, which



(a)



(b)

Figure 9. Settlement behaviors of tunnel segment under different water pressure, where pw represents water pressure: (a) the results for fractured surrounding rock and (b) the results for intact surrounding rock.

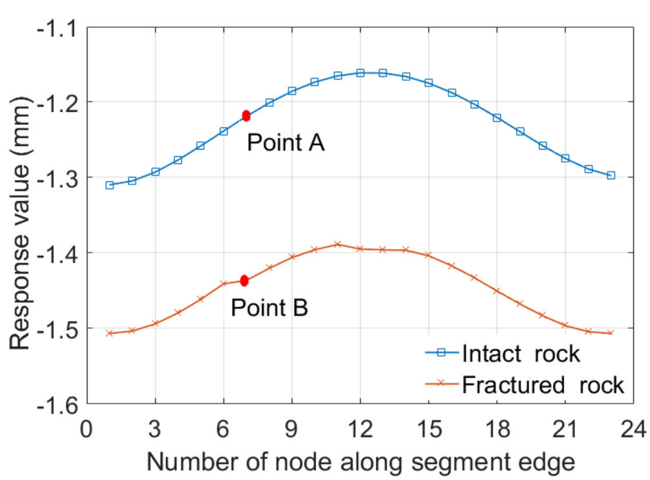


Figure 10. The response value of tunnel settlement when the water level changed 1 m.

means that the response of tunnel settlement to water pressure is continuous. On the contrary, there are several discontinuous points in the response curve of fractured rock, and they are located at the intersection of factures and tunnel segment.

To verify the numerical results obtained from our presented model, some feature points were selected for field verification, as highlighted red in Figure 11. The response value of tunnel settlement in fractured surrounding rock is 1.445 mm, but that in intact rock mass is 1.221 mm under the specified variation of water level.

5. Model verification using field monitoring results

To investigate the stability of underwater shield tunnel, a structural health monitoring system (SHMS) was installed in the Nanjing Yangtze River tunnel to have a real-time monitoring of its mechanical behaviors. Basing on the mass monitoring data, an analytical model was performed to verify the numerical results obtained from the presented DFNs model.

5.1. Monitoring scheme and results for the study site

The SHMS installed in the Nanjing Yangtze River tunnel consists of three components, data acquisition and transmission, center database, and smart user system, which has been introduced in detailed in our previous work (Tan et al. 2019). Considering the variation of water pressure, soil pressure, the position of work well, and the complex geological conditions, ten monitoring sections were employed in this project, including two monitoring sections located in research areas. Specifically, the distance between these two monitoring sections in research areas is 10 m. Many sensors have been installed in field to monitor the mechanical behaviors of tunnel. The hydrostatic leveling sensors, installed in cable way to correspond with the positions of feature points, were used to have a real-time monitoring of the variation of tunnel settlement. Furthermore, the water pressure sensors were also installed near the hydrostatic leveling sensor to monitor the water pressure applied on tunnel structure. The layout of these monitoring sensors is shown in Figure 11, and their operation parameters are shown in Table 4.

The central database was established to store the mass number of real-time and historical monitoring data, and the monitoring data were transferred to it through optical fiber cables. Thus, based on the SHMS system, the monitoring data from April 1, 2018 to March 20, 2019 are collected as examples displayed in Figure 12.

The Figure 12a shows the monitoring results of tunnel settlement, it can be observed that the settlement performance occurred in the study area. There are few differences of settlement behaviors between S1 and S2 due to the similarity between their geological conditions, and the magnitudes of settlement in these monitoring sections are up to 1.2 cm. In addition, the displacement of tunnel settlement varied with seasons, which increased from June to October, and then decreased gradually. This law was consistent with that of water pressure, as shown in Figure 12b. Therefore, the variation of water pressure has great importance on tunnel settlement. In order to maintain the stability of tunnel, it is vitally important to analyze the response of tunnel settlement to the variation of water pressure applied on structure.

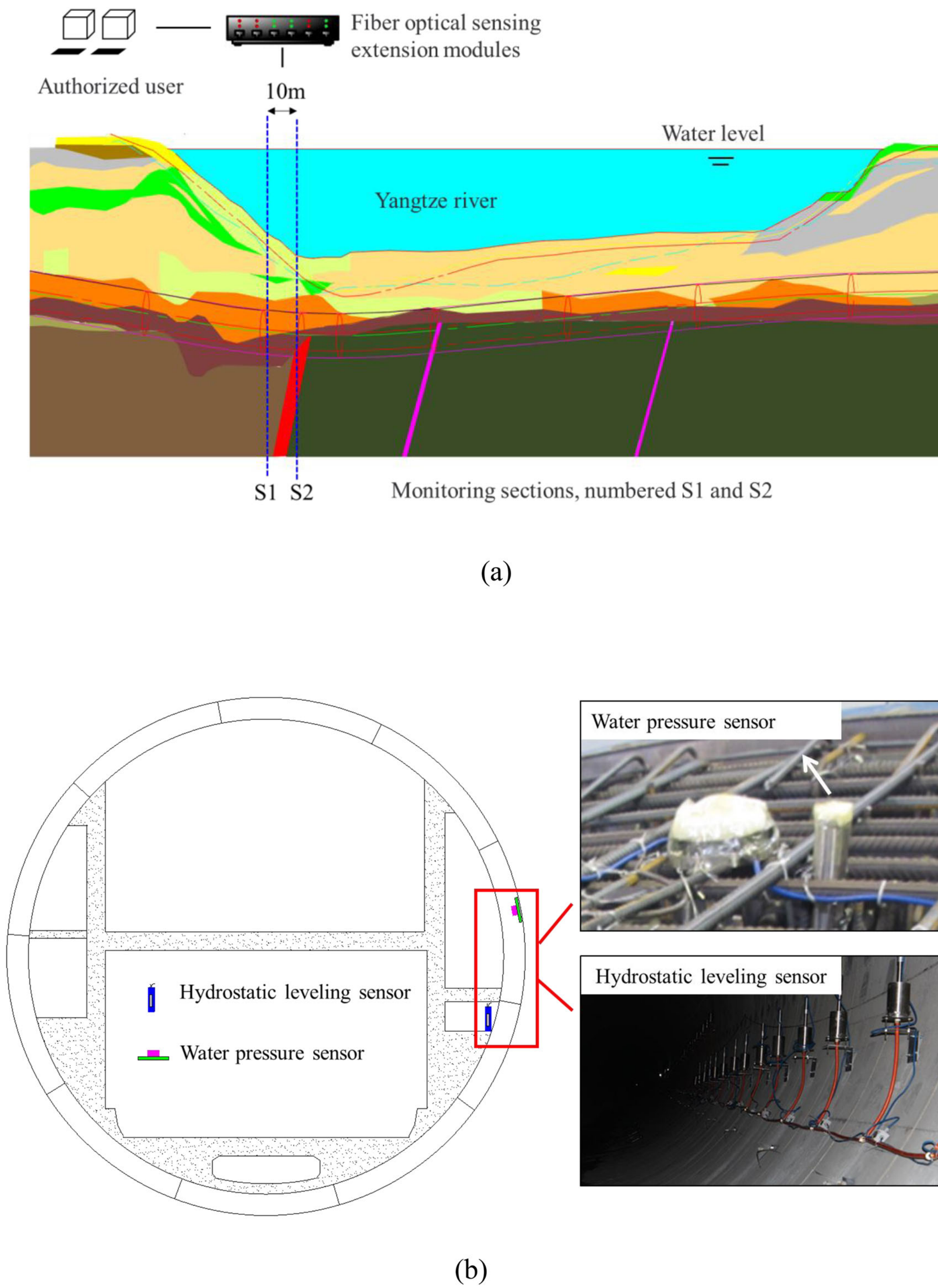


Figure 11. The monitoring scheme in field: (a) location of monitoring sections in research area, and (b) layout of sensors in a monitoring section.

5.2. Verification of the numerical model and comparison with field monitoring data

To analyze the response of tunnel settlement to the variation of water pressure, an analytical model for the Nanjing Yangtze River tunnel was setup based on the mass number of monitoring data. The existing researches have denoted that the statistic theory was widely used in processing mass number of monitoring data and acquiring valuable information of structure mechanical behaviors (Johnson and Wichern 2014; Draper and Smith 2014). In our previous works, the multiple linear regression models, developed on the basis of statistic theory were carried out to analyze the mechanical behaviors of segment

Table 4. The measurement parameters of sensors.

Sensors	Measuring range	Precision	Sensitivity	Interval
Hydrostatic leveling sensor	100mm	$\leq$1.0%FS	0.1%FS	12h
Water pressure sensor	1MPa	$\leq$1.0%FS	0.1%FS	12h

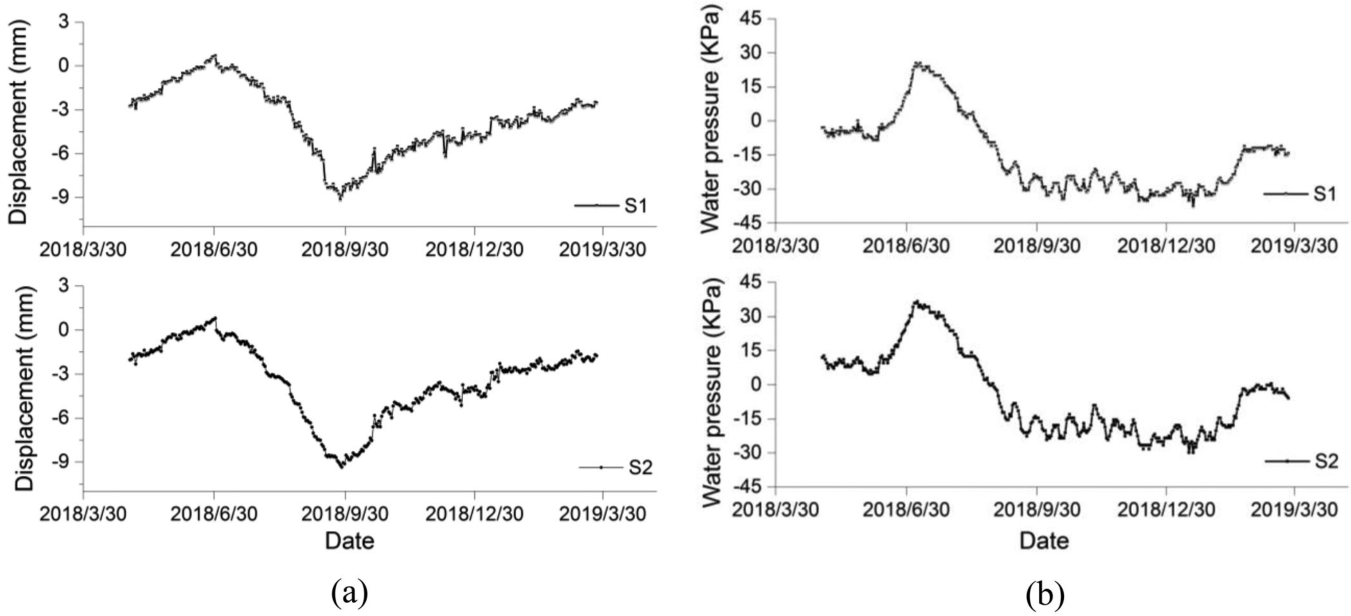


Figure 12. The real-time monitoring data obtained from SHMS: (a) displacement of tunnel settlement, and (b) variation of water pressure.

Table 5. Values of response obtained from different model.

	Numerical model		Analytical model
Model	Intact rock	Fractured rock	Field monitoring
Displacement of uneven settlement	1.22 mm	1.45 mm	1.70 mm

strain and joint opening, and the analytical results agreed well with the actual conditions (Tan et al. 2019). The displacement of uneven settlement was regarded as dependent variable, while the water pressure of the Nanjing Yangtze river tunnel was regarded as independent variable. The analytical model was developed as follow:

$$D = \beta_0 + \beta_1 H + \varepsilon \tag{8}$$

where D is the displacement of uneven settlement, β_1 is water pressure regression parameter, and H is water pressure.

The parameter β_1 represents the response value of settlement to the variation of water pressure. In the light of Equation (8), the analytical model was used to analyze the response of feature points. Based on the monitoring data displayed in Figure 12, the value of parameter β_1 was calculated through our developed MATLAB code. If the water level varied 1 m, the analytical results changes correspondingly, as shown in Table 5. Compared with the results obtained from different numerical models, which are also displayed in this table, it is easy to find that the field monitoring results agree better with the numerical results calculated by DFNs model. This result indicated the presented DFNs model is more reliable. Since the effect of water pressure is little and can be ignored, the error is from the influence of other constrains among segments on the tunnel settlement.

6. Conclusions

An integrated framework was developed in this study to analyze the influence of discrete fractures on tunnel settlement, which consists of numerical simulation, field monitoring, and theoretical analysis. The Nanjing Yangtze River tunnel, a typical underwater shield tunnel excavated in a fractured surrounding rock is selected as a case study. The main conclusions are presented as follows:

1. A stochastic fracture model was introduced based on the improved hybrid finite element method. It was used to construct the geometry of the multiple fractures. Compared with most previous models, this model considers the real width of fractures, and the fractured elements could be used to simulate the mechanical behaviors of fractures. Also, the rock and factures were discretized into triangular elements and quadrilateral elements, respectively. The problems of element generation at intersection point between multi-fractures are solved.
2. The developed numerical model was applied to analyze the settlement behaviors of Nanjing Yangtze River tunnel under different boundary conditions. It denoted that the increase of water pressure caused the upward movement of arch bottom, and settlement of arch crown. As a comparison, a numerical model whose surrounding rock is intact is setup. It can be found that there are some differences between these two conditions. The displacement of settlement in fractured rock is larger than that obtained from intact rock model. The value of former is 1.45 mm, and that of later is 1.22 mm when the water level changed 1 m.
3. To verify the reliability of numerical results, a structural health monitoring system (SHMS) was employed in site to have a real-time monitoring of structural mechanical behaviors. Based on the mass monitoring data, an analytical model was introduced to study the response of tunnel settlement to water pressure. It is obvious that the analytical results are closer to the numerical results obtained from DFNs model. It means the presented

model is reasonable and it is important to consider the impact of fractures on settlement behaviors.

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