symmetry

MDPI

Article

Resilience Evaluation of the Existing Shield Tunnel Lining Induced by the Symmetrical Excavation of Adjacent Foundation Pit Based on Numerical Simulations

Long Jiang * and Shengyue Hao

School of Economics and Management, Beijing Jiaotong University, Beijing 100044, China; haoshyue@bjtu.edu.cn
* Correspondence: 18113063@bjtu.edu.cn

Abstract: It is very important to evaluate the structural behavior of shield tunnel lining reasonably to ensure the safe operation and maintenance of subway trains. In this paper, by virtue of the resilience theory, the resilience evaluation of the existing shield tunnel lining induced by the symmetrical excavation of adjacent foundation pit is conducted using the numerical simulation. Firstly, the structural behavior index of the shield tunnel lining is defined. Moreover, using the evolution of structural behavior index along with the symmetrical excavation steps of adjacent foundation pit, the calculation method of the resilience index of the shield tunnel lining and grade of resilience are proposed. Secondly, numerical simulation is conducted to compare the degree of influence of three different block symmetrical excavation methods of the adjacent foundation pit on the structural deformation of existing shield tunnel lining. Finally, based on the proposed resilience evaluation method, the structural deformation index and the resilience index of the existing shield tunnel lining are calculated under three different block symmetrical excavation methods, which indicates that the control effect of different block symmetrical excavation methods of the adjacent foundation pit varies greatly. Moreover, it is necessary to adopt the fine excavation method of foundation pit by sections to better control the deformation of the existing shield tunnel lining.

Keywords: shield tunnel; foundation pit; longitudinal deformation; block symmetrical excavation; structural behavior index; resilience index

Citation: Jiang, L.; Hao, S. Resilience Evaluation of the Existing Shield Tunnel Lining Induced by the Symmetrical Excavation of Adjacent Foundation Pit Based on Numerical Simulations. *Symmetry* **2022**, *14*, 229. https://doi.org/10.3390/sym14020229

Academic Editor: Chiara Bedon

Received: 19 December 2021
Accepted: 19 January 2022
Published: 25 January 2022

1. Introduction

To ensure the safe operation and maintenance of subway trains, there are strict deformation control requirements for metro shield tunnels. With the density of subway networks, adjacent excavation has become an important hidden danger of the safe operation of subway tunnels. The excavation and unloading around the subway tunnel will inevitably lead to changes in the soil stress state within a certain range around the excavation, which will cause additional stress in the shield tunnel lining. In serious cases, the cracking and water leakage of tunnel segments will be caused, threatening the safety of subway operation.

Traditionally, many scholars have carried out a lot of research on segment evaluation of shield tunnels, mainly using specific indicators of the shield tunnel lining, such as convergence deformation value, joint opening amount, concrete crack width, etc., to evaluate the safety state of the tunnels and then give corresponding suggestions [1–6]. Based on the measured data of the deep foundation pit of an adjacent tunnel in Tianjin, Zheng et al. [7] calculated and analyzed the division of the affected zone of the existing tunnel deformation outside the pit. The results show that under the same maximum horizontal deformation and tunnel displacement control standard, the influence area of cantilever deformation is the smallest. Huang et al. [8] found that when the upper foundation pit was excavated, the underlying tunnel would have obvious upward floating deformation, and its influence range was twice the excavation width beyond the excavation boundary. In addition, the study also shows that it is very important to select appropriate measures to control tunnel deformation and strengthen tunnel segments to reduce the impact of foundation pit excavation. Liu et al. [9] studied the technology of epoxy resin bonding fiber to reinforce tunnels, which shows that the influence of foundation pit excavation can be reduced by increasing the stiffness of the tunnel. Yang et al. [10] applied a new composite structure to a tunnel segment and analyzed the mechanical behavior and failure mode of the segment reinforced by the composite structure in detail through tests.

Recently, since the resilience can reflect the systemic changes of the whole process in relation to time, it has been adopted by many scholars to evaluate the state of studied system [11–20]. Huang and Zhang [21] considered that there should be an evolution stage between the disturbance stage and the recovery stage after a disaster and established a model suitable for evaluating the resilience of shield tunnel lining. However, there is very little literature on the subject of the resilience evolution analysis of the existing shield tunnels induced by the influence of adjacent foundation pit excavations based on numerical simulations.

Based on resilience theory, an analysis of the resilience evolution of the existing shield tunnels induced by the symmetrical excavation of an adjacent foundation pit is conducted by virtue of numerical simulation. Firstly, the definitions of structural deformation index and the resilience index of the shield tunnel lining are proposed. Secondly, the Plaxis 3D finite element software is used to carry out the comparative analysis of the degree of influence of three different block symmetrical excavation methods of an adjacent foundation pit on the structural deformation of the shield tunnel lining. Finally, based on the proposed resilience evaluation method, the structural deformation index and the resilience index of the existing shield tunnel lining under three different block symmetrical excavation methods are calculated and studied.

2. Resilience Evaluation of Tunnel Lining

2.1. Structural Behavior Index

In order to ensure the safe operation of subway trains, the deformation control standard of the subway tunnel lining is very strict. For instance, Chinese Standard CJJ/T202-2013 [22] states that the following indicators need to meet specific conditions: an absolute settlement and horizontal displacement of station and shield tunnel lining $\leq$ 20 mm; a differential settlement of deformation joints $\leq$ 10 mm; a curvature radius of tunnel longitudinal deformation curve $\geq$ 15,000 m; and a relative deflection of the tunnel $\leq$ 1/2500. Thus, to characterize the safety degree of tunnel lining deformation, the structural behavior index is defined as the ratio of the difference between structural deformation of tunnel lining and specified warning value in the Chinese Standard CJJ/T202-2013 to the warning value, as shown in Equation (1):

$$Q = \frac{\omega_{\max} - \omega}{\omega_{\max}} \tag{1}$$

where Q denotes the structural behavior index; $\omega_{\max}$ presents the specified warning value in the Chinese Standard CJJ/T202-2013; and ω is the structural deformation of tunnel lining.

2.2. Index and Grade of Resilience

Due to the time effect of soil deformation, the block excavation with several steps of an adjacent foundation pit is beneficial to control the deformation of the existing tunnel. The evolution curves of structural behavior index Q versus steps i under different excavation plans of the foundation pit are displayed in Figure 1. Furthermore, the resilience index of tunnel lining R is proposed by ratio of the area (evolution curves of structural behavior index) to initial curve S_0, as rendered in Equation (2):

$$R = \frac{\sum_1^i S_i}{S_0} = \frac{\sum_1^i \frac{Q_i + Q_{i-1}}{2}}{Q_0 \Sigma i} \tag{2}$$

where R denotes the resilience index of the tunnel lining; S_0 presents the area bounded by the initial curve Q_0 and the horizontal axis; and S_i depicts the area bounded by curve $Q_i Q_{i-1}$ and the horizontal axis (c.f. Figure 1).

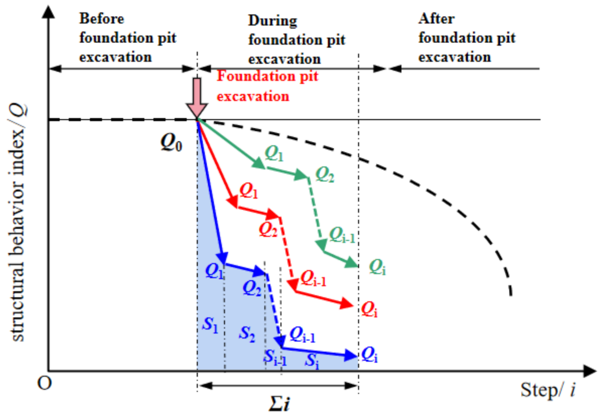


Figure 1. The evolution curves of structural behavior index Q versus steps i under different excavation plans of the foundation pit.

Based on the range of values of the resilience index of the tunnel lining R, the grade of resilience is proposed as exhibited in Table 1, which indicates the influence degree of the excavation of adjacent foundation pit on existing shield tunnel lining. In general, the influence degree for High Resilience is the least, the influence degree of Moderate Resilience is second, and the influence degree of Low Resilience is the greatest.

Table 1. Grade of resilience.

Grade	Range	Colour
High Resilience	$0.8 \leq R < 1.0$	(green)
Moderate Resilience	$0.6 \leq R < 0.8$	(yellow)
Low Resilience	$R < 0.6$	(red)

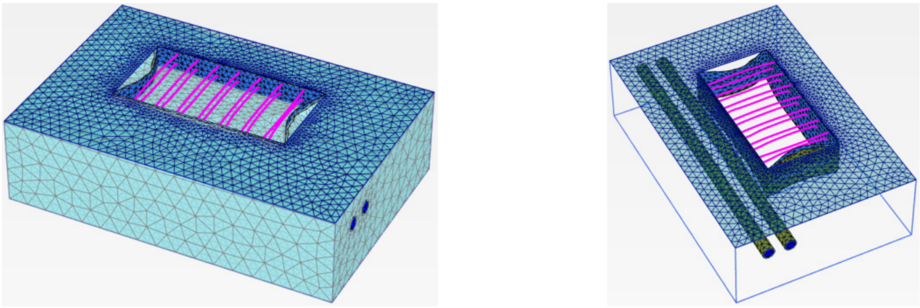
3. Numerical Model and Procedure

3.1. Numerical Procedure

PLAXIS 3D is a widely used geotechnical engineering finite element software, which can simulate complex engineering geological conditions, structures and construction processes, especially suitable for deformation analysis. The overall model and relative position relation between a symmetrical excavation pit and existing tunnels are shown in Figure 2. The dimensions and meshes of the numerical simulation model are as follows: The length of the model is 150 m, the width of the model is 100 m, the height of the model is 50 m; the diameter of the tunnel is equal to the outer diameter of the cutter plate 6.2 m, and the depth of the stratum below the tunnel bottom is 12 m, as shown in Figure 2. The length direction of the foundation pit is 100 m, the width direction is 40 m, and the depth is 30 m. The foundation pit is only 3 m from the nearest point of the tunnel. In addition to the free surface at the top of the model, deformation constraints are applied around and at the bottom. The soil material in the calculation follows the Mohr–Coulomb failure criterion. Table 2 renders the soil parameters.

3.2. Block Excavation Condition Setting of Foundation Pit

In this paper, three different excavation plans for the foundation pit with several steps are adopted to investigate the influence degree of the excavation of adjacent foundation pit on existing shield tunnel lining. As illustrated in Figure 3, Plan 1 indicates that the foundation pit is excavated longitudinally and layered by sections, Plan 2 renders that the foundation pit is excavated transversely and layered by sections and Plan 3 shows that the foundation pit is excavated transversely (more sophisticated) and layered by sections.

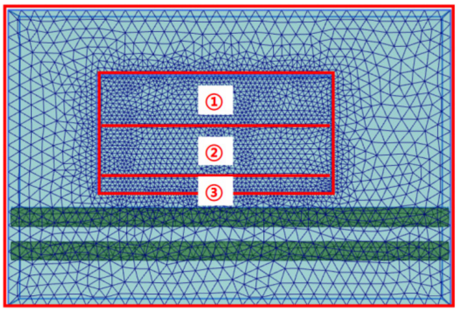


(**a**) (**b**)

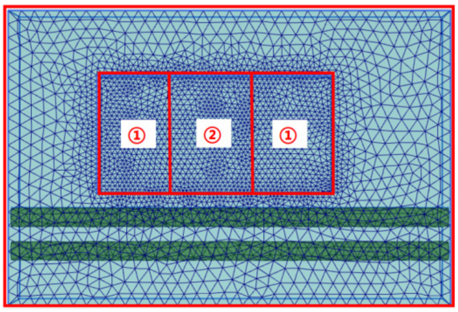
Figure 2. Numerical simulation model: (**a**) Overall model; (**b**) relative position relation between adjacent foundation pit and existing tunnels.

Table 2. Soil parameters.

Parameters	Symbol	Mucky Clay
Saturated unit weight	γ_{sat} [kN/m^3]	16.8
Elasticity modulus	E [kN/m^2]	4045
Poisson's ratio	ν (nu)	0.2
Cohesion	c [kN/m^2]	20
Internal friction angle	φ (phi) [°]	23.7
Lateral pressure coefficient	K_0	0.5981

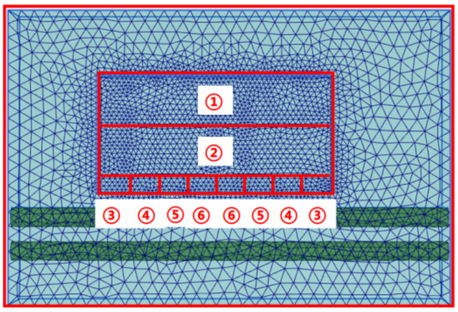


(**a**)



(**b**)

Figure 3. *Cont.*



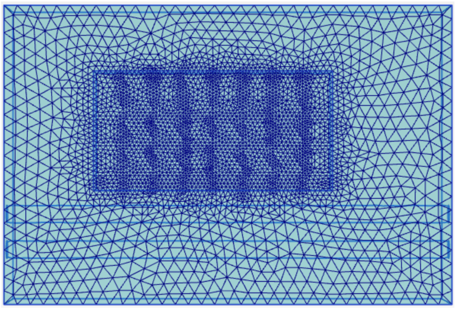
(**c**)

Figure 3. Three different excavation plans of foundation pit with several steps: (**a**) Plan 1; (**b**) Plan 2; (**c**) Plan 3.

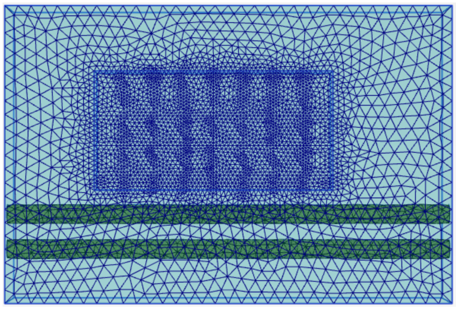
4. Numerical Results and Analyses

4.1. Typical Results of Deformation Response of Existing Tunnel (Plan 3)

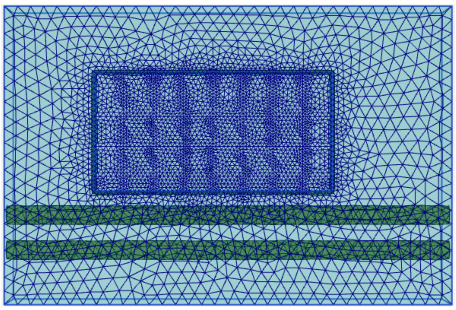
Figure 4 shows the contour of the displacement response of the existing tunnel under different steps (Scale = 30). With the block symmetrical excavation of the foundation pit and the construction of the supporting structure, the deformation of the tunnel structure tends to one side of the foundation pit.



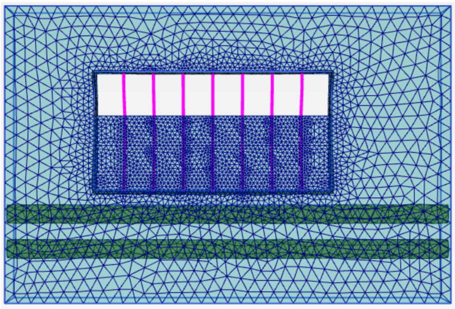
(**a**)



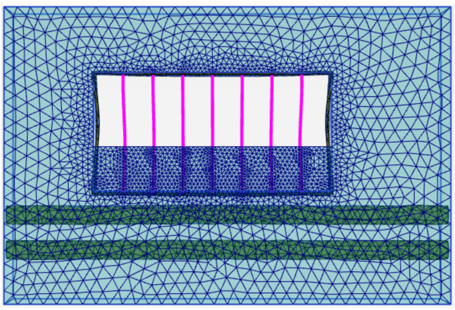
(**b**)



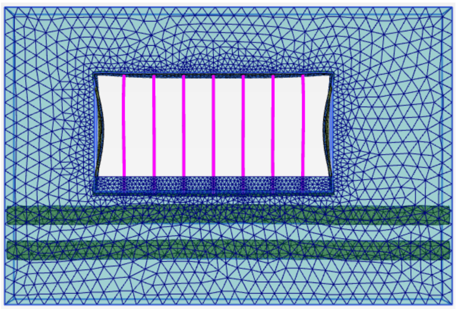
(**c**)



(**d**)

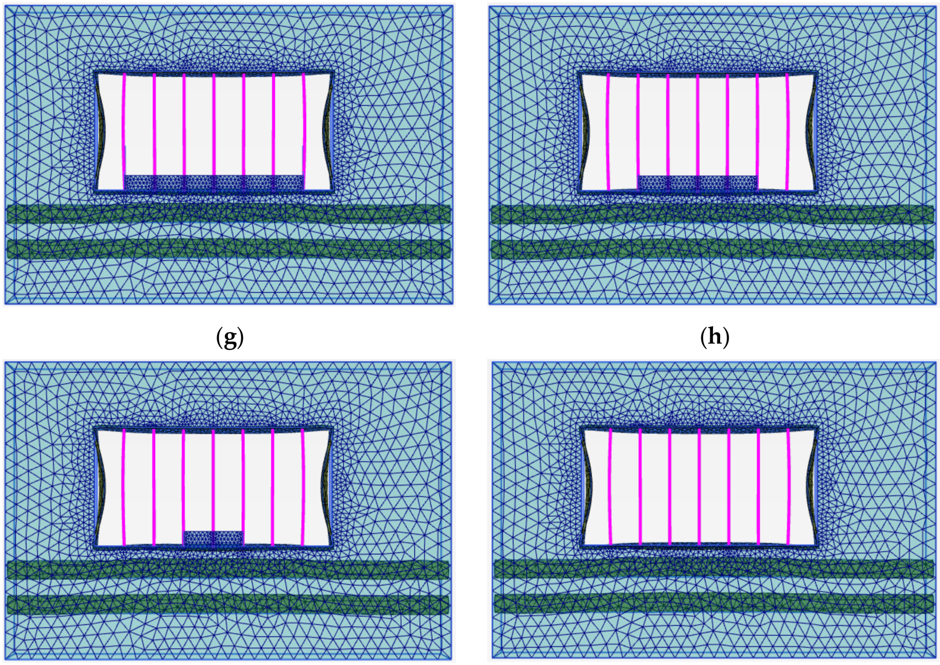


(**e**)



(**f**)

Figure 4. *Cont.*

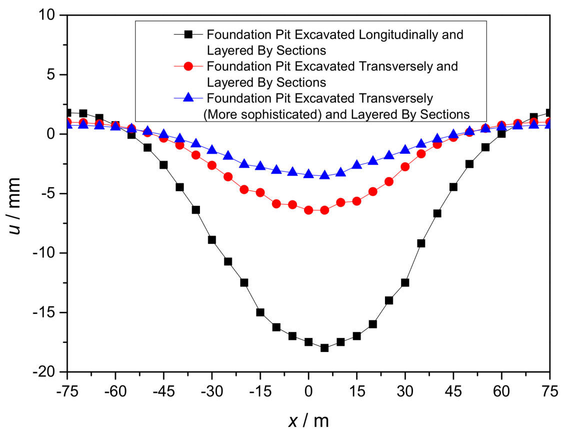


(**g**) (**h**)

(**i**) (**j**)

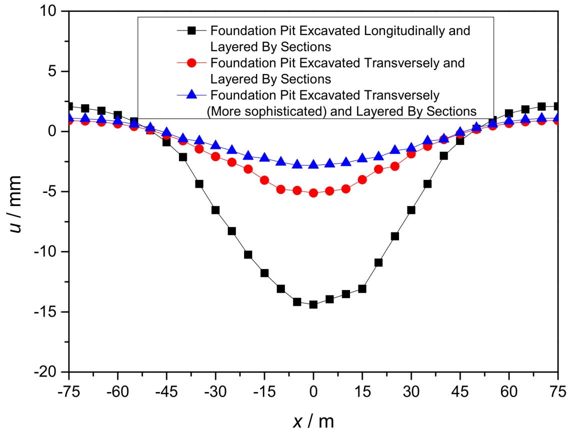
Figure 4. Contour of displacement response of existing tunnel under different steps (Scale = 30): (**a**) initial state; (**b**) tunnel excavation; (**c**) construction of retaining structure of foundation pit; (**d**) the first block in the first layer; (**e**) the second block in the first layer; (**f**) the third block in the first layer; (**g**) the fourth block in the first layer; (**h**) the fifth block in the first layer; (**i**) the sixth block in the first layer; (**j**) the seventh block in the first layer.

The traditional analysis method focuses on the longitudinal deformations of the existing tunnel when the foundation pit was excavated with three diagrams of the block symmetrical excavation of foundation pit, as shown in Figure 5. The results show that the longitudinal deformations of the existing shield tunnel linings vary greatly under different symmetrical excavation methods. When plan 1 is used to excavate the foundation pit, the longitudinal deformations of the existing shield tunnel lining increase the most. When plan 2 is adopted, the degree of the longitudinal deformations is second. When plan 3 is adopted, the longitudinal deformations of the existing shield tunnel lining increase to the minimum. Moreover, because the existing tunnel on the right line is far from the foundation pit, the longitudinal deformation variation trend of the existing tunnel on the right line under the three symmetrical excavation plans is lower than that of the existing tunnel on the left line.



(**a**)

Figure 5. *Cont.*



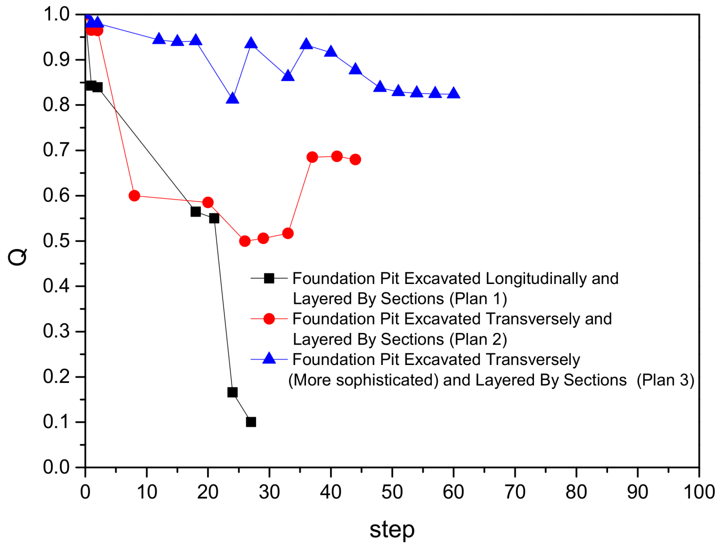
(**b**)

Figure 5. Longitudinal deformations of existing tunnel when foundation pit was excavated with three diagram of block excavation of foundation pit: (**a**) left line; (**b**) right line.

4.2. Performance Status Evolution and Resilience Evaluation of Tunnel Lining

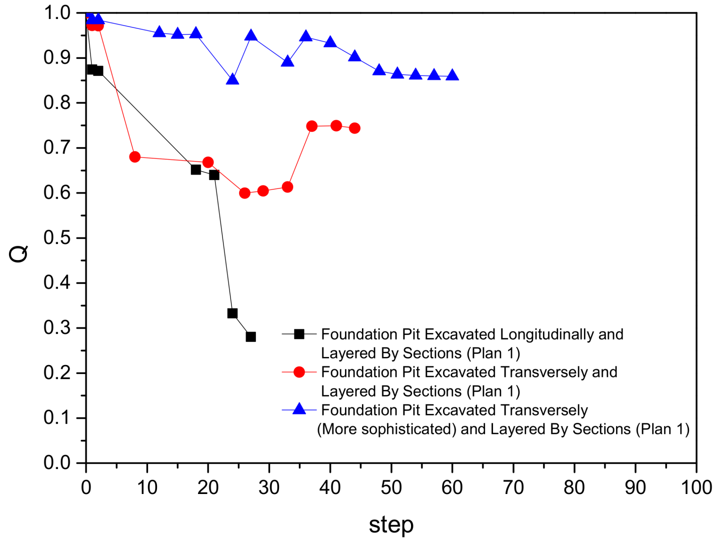
The above is the result of the traditional analysis method, which has the following two disadvantages. On the one hand, although the traditional method can see the deformation laws of the existing tunnel on the whole, it cannot directly see the proximity of the deformation distance of the existing tunnel to the warning value required by the Chinese Standard CJJ/T202-2013. On the other hand, traditional analysis methods cannot directly compare the disturbance safety grade of different excavation methods.

Therefore, the performance status evolution and resilience evaluation of shield tunnel lining are carried out by using the proposed Equations (1) and (2). Figure 6 shows the performance status evolution of the existing tunnels when the foundation pit was excavated with three diagrams of the block symmetrical excavation of foundation pit. When plan 1 is used to excavate the foundation pit, the structural behavior index Q decreases the most. When plan 2 is adopted, the decrease degree of the structural behavior index Q is second. When plan 3 is adopted, the structural behavior index Q decreases to the minimum. Moreover, because the existing tunnel on the right line is far from the foundation pit, the decrease degree of sthe tructural behavior index Q on the right line under the three symmetrical excavation plans is lower than that of the existing tunnel on the left line.



(**a**)

Figure 6. *Cont.*



(**b**)

Figure 6. Performance status evolution of existing tunnel when foundation pit was excavated with three diagram of block symmetrical excavation of foundation pit: (**a**) left line; (**b**) right line.

Furthermore, the resilience evaluation of the shield tunnel lining is displayed in Table 3. It can be seen from the value of the resilience index that the resilience index of the existing shield tunnel lining varies greatly under different symmetrical excavation methods. The resilience index of the existing shield tunnel lining is the smallest when the first plan is adopted. When plan 2 is used to excavate the foundation pit, the value of the resilience index will increase. When plan 3 is adopted, the resilience index of the existing shield tunnel lining is the largest. Similarly, because the existing tunnel on the right line is far from the symmetrical excavation pit, the resilience index value of the existing tunnel on the right line under the three symmetrical excavation plans is higher than that of the existing tunnel on the left line.

Table 3. Resilience evaluation of tunnel lining.

Resilience Grade	Plan 1	Plan 2	Plan 3
Left line	0.59	0.63	0.89
Right line	0.67	0.70	0.91

5. Conclusions

In this paper, based on resilience theory, the analysis of the resilience evolution of the existing shield tunnels induced by the symmetrical excavation of an adjacent foundation pit is conducted by virtue of numerical simulations. The main conclusions are as follows:

The definitions of the structural deformation index and the resilience index of the shield tunnel lining proposed in this paper are good indicators to analyze the influence degree of the symmetrical excavation of an adjacent foundation pit on the existing shield tunnels.

The analysis of the performance status evolution of existing tunnels when a foundation pit was excavated with three diagrams of the block symmetrical excavation of foundation pit indicates that when plan 1 is used to excavate the foundation pit, the structural behavior index decreases the most. When plan 2 is adopted, the decrease degree of the structural behavior index is second. When plan 3 is adopted, the structural behavior index decreases to the minimum.

The analysis of the resilience evaluation of the shield tunnel lining shows that the resilience index of the existing shield tunnel lining varies greatly under different symmetrical excavation methods. Moreover, because the existing tunnel on the right line is far from the symmetrical excavation pit, the resilience index value of the existing tunnel on the right line under the three symmetrical excavation plans is higher than that of the existing tunnel on the left line. It is necessary to adopt the fine symmetrical excavation method of the foundation pit by sections to better control the deformation of the existing shield tunnel lining.

Author Contributions: Conceptualization, L.J. and S.H.; methodology, L.J.; software, L.J.; validation, L.J. and S.H.; formal analysis, L.J.; investigation, L.J.; resources, L.J.; data curation, L.J.; writing—original draft preparation, L.J.; writing—review and editing, S.H.; visualization, S.H.; supervision, S.H.; project administration, S.H.; funding acquisition, S.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No. 51978042).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors are deeply thankful to the reviewers and editor for their valuable suggestions to improve the quality of the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hu, H.Y.; Zhang, Y.C.; Yang, G.H.; Zhong, Z.H.; Chen, F.Q. Measurement and numerical analysis of effect of excavation of foundation pits on metro tunnels. *Yantu Gongcheng Xuebao/Chin. J. Geotech. Eng.* **2014**, *36*, 431–439.
2. Wei, G. Measurement and analysis of impact of foundation pit excavation on below existed shield tunnels. *Yantu Lixue/Rock Soil Mech.* **2013**, *34*, 1421–1428.
3. Ng, C.W.W.; Shi, J.; Hong, Y. Three-dimensional centrifuge modelling of basement excavation effects on an existing tunnel in dry sand. *Can. Geotech. J.* **2013**, *50*, 874–888. [CrossRef]
4. Zhang, Z.G.; Huang, M.S.; Wang, W.D. Responses of existing tunnels induced by adjacent excavation in soft soils. *Yantu Lixue/Rock Soil Mech.* **2009**, *30*, 1373–1380.
5. Nikan, O.; Avazzadeh, Z. Coupling of the Crank–Nicolson scheme and localized meshless technique for viscoelastic wave model in fluid flow. *J. Comput. Appl. Math.* **2021**, *398*, 113695. [CrossRef]
6. Nikan, O.; Avazzadeh, Z. A localisation technique based on radial basis function partition of unity for solving Sobolev equation arising in fluid dynamics. *Appl. Math. Comput.* **2021**, *401*, 126063. [CrossRef]
7. Zheng, G.; Du, Y.M.; Diao, Y.; Deng, X.; Zhu, G.P.; Zhang, L.M. Influenced zones for deformation of existing tunnels adjacent to excavations. *Yantu Gongcheng Xuebao/Chin. J. Geotech. Eng.* **2016**, *38*, 599–612.
8. Huang, X.; Schweiger, H.F.; Huang, H. Influence of deep excavations on nearby existing tunnels. *Int. J. Geomech.* **2013**, *13*, 170–180. [CrossRef]
9. Liu, X.; Jiang, Z.; Zhang, L. Experimental investigation of the ultimate bearing capacity of deformed segmental tunnel linings strengthened by epoxy-bonded filament wound profiles. *Struct. Infrastruct. Eng.* **2017**, *13*, 1–16. [CrossRef]
10. Yang, C.; Yan, Z.; Shen, Y.; Zhu, H.; Tang, Z. Experimental investigation on the mechanical behavior and failure form of RC segment reinforced with a new composite structure. In Proceedings of the China: 2014 Geoshanghai International Congress Shanghai, Shanghai, China, 26–28 May 2014.
11. Bruneau, M.; Chang, S.E.; Eguchi, R.T.; Lee, G.C.; O'Rourke, T.D.; Reinhorn, A.M.; Shinozuka, M.; Tierney, K.; Wallace, W.A.; Von Winterfeldt, D. A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthq. Spectra* **2003**, *19*, 733–752. [CrossRef]
12. Bruneau, M.; Reinhorn, A. Exploring the concept of seismic resilience for acute care facilities. *Earthq. Spectra* **2007**, *23*, 41–62. [CrossRef]
13. Chang, S.E.; Shinozuka, M. Measuring improvements in the disaster resilience of communities. *Earthq. Spectra* **2004**, *20*, 739–755. [CrossRef]
14. Cimellaro, G.P.; Reinhorn, A.M.; Bruneau, M. Framework for analytical quantification of disaster resilience. *Eng. Struct.* **2010**, *32*, 3639–3649. [CrossRef]
15. Ouyang, M.; Dueñas-Osorio, L.; Min, X. A three-stage resilience analysis framework for urban infrastructure systems. *Struct. Saf.* **2012**, *36–37*, 23–31. [CrossRef]
16. Turnquist, M.; Vugrin, E. Design for resilience in infrastructure distribution networks. *Environmentalist* **2013**, *33*, 104–120. [CrossRef]
17. Francis, R.; Bekera, B. A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliab. Eng. Syst. Saf.* **2014**, *121*, 90–103. [CrossRef]

18. Ayyub, B.M. Systems resilience for multihazard environments: Definition, metrics, and valuation for decision making. *Risk Anal.* **2014**, *34*, 340–355. [CrossRef] [PubMed]
19. Ahmadi, S.; Saboohi, Y.; Vakili, A. Frameworks, quantitative indicators, characters, and modeling approaches to analysis of energy system resilience: A review. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110988. [CrossRef]
20. Mottahedi, A.; Sereshki, F.; Ataei, M.; Qarahasanlou, A.N.; Barabadi, A. Resilience estimation of critical infrastructure systems: Application of expert judgment. *Reliab. Eng. Syst. Saf.* **2021**, *215*, 107849. [CrossRef]
21. Huang, H.W.; Zhang, D.M. Resilience analysis of shield tunnel lining under extreme surcharge: Characterization and field application. *Tunn. Undergr. Space Technol.* **2016**, *51*, 301–312. [CrossRef]
22. Ministry of Housing and Urban-Rural Construction of the People's Republic of China. *Technical Chinese Standard for the Prctection Structures of Urban Rail Transit (CJJ/T202-2013)*; China Construction Industry Press: Beijing, China, 2014. (In Chinese)