

Water Inrush Hazard in Shijingshan Tunnel during Construction, Zhuhai, Guangdong, China

He-Qi Kong, Lin-Shuang Zhao * and Ning Zhang * 

MOE Key Laboratory of Intelligence Manufacturing Technology, Department of Civil and Environmental Engineering, College of Engineering, Shantou University, Shantou 515063, China; 21hqkong@stu.edu.cn
* Correspondence: lshzhao@stu.edu.cn (L.-S.Z.); zhangning@stu.edu.cn (N.Z.); Tel.: +86-754-8650-4551 (N.Z.)

Abstract: This short communication reports a water inrush hazard during the construction of the Shijingshan Tunnel in Zhuhai, Guangdong, China. On 15 July 2021, a water inrush accident occurred at the construction site 1.16 km away from the tunnel entrance, resulting in 14 casualties. The purpose of this study is to investigate and discuss the water inrush process in this atypical case. The principal causes of this tunneling accident include the special geological conditions at the construction site, high hydraulic conductivity at the part that connects the underground water system and the overlying water body (the Jida Reservoir), and the impact of heavy rainfall. Moreover, four significant suggestions are proposed to prevent the possible occurrence of water inrush disaster: (1) assessing the risk level in areas prone to water inrush; (2) getting a comprehensive geological prediction based on borehole data and artificial intelligent methods; (3) establishing a monitoring system during the tunneling process; (4) strengthening the self-protection skills of construction workers.

Keywords: tunnel water inrush; investigation; rescue; countermeasures



Citation: Kong, H.-Q.; Zhao, L.-S.; Zhang, N. Water Inrush Hazard in Shijingshan Tunnel during Construction, Zhuhai, Guangdong, China. *Safety* **2022**, *8*, 7. <https://doi.org/10.3390/safety8010007>

Academic Editor: Raphael Grzebieta

Received: 23 November 2021

Accepted: 25 January 2022

Published: 29 January 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In recent decades, the construction of infrastructure and facilities has been booming in China, such as tunnels [1], excavations [2], metro systems [3], et al. Nevertheless, during the construction process of these infrastructures and facilities, many human engineering activities resulted in accidents and environmental issues. For example, excavation collapse [4–6], water inrush hazards in tunnels [7,8], bridge or building collapse [9] and water pollution [10], which significantly affect the safety of the society and citizens. For instance, on June 10, 2018, water inrush hazards in the Chaoyang Tunnel caused three casualties and many injuries [11]. Excluding human-related factors [12,13], natural factors including earthquake [14], heavy rainfall and tornadoes [15] are also of significance to the safety of infrastructures during the urbanization process. In order to prevent the infrastructures from hazards, many researchers have investigated the mechanism of hazards and developed various methods for risk assessments [16,17] and disaster prediction [18]. The associated methods include an analytic hierarchy process (AHP) [19], Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) [20,21], numerical method [22] and artificial intelligence [23]. In addition, efforts are also taken for the optimization of construction techniques [24–27]. Risk assessment is a comprehensive safety estimation for target engineering projects and related environments [28], which are very important for warning system and rescue operation for these hazards. Among aforementioned hazards, water inrush in tunnels tends to cause serious adverse effects since they cannot be easily detected in advance. Hence, investigation on water inrush hazards is necessary based on a geological survey, surrounding environment and annual weather conditions.

This short communication reports a catastrophic water inrush accident in Zhuhai, Guangdong Province [29,30]. The first section presents the main information of the tunneling project. The following section describes the water inrush accident and the subsequent

rescue operation. After that, we analyzed the influencing factors related to the development of this hazard. Finally, an effective monitoring system and risk assessment are essential for water inrush prone areas.

2. Background

Figure 1 shows the site location map of the collapsed tunnel. The project in this study is the Xingye Expressway (south section) underneath the north of Banzhangshan Mountain in Zhuhai, Guangdong, China (Figure 1a). The studied area consists of two tunnels (east and west tunnels) starting from the intersection of Jiuzhou Avenue and Jianye 1st Road in the south, ending at the working well in the north of Banzhangshan, with a total length of approximately 2.5 km (Figure 1b). The lengths of the west and east lines are 2445.9 m and 2434.4 m, respectively. The designed height of the tunnel is 11 m, and the width is 15 m. The tunnels adopted the New Austrian Tunnelling Method (NATM) with bench cut approach. The support system should contain advanced support pipes of $\Phi 42 \times 4$ with grouting, anchors support, steel arch and grouting concrete.

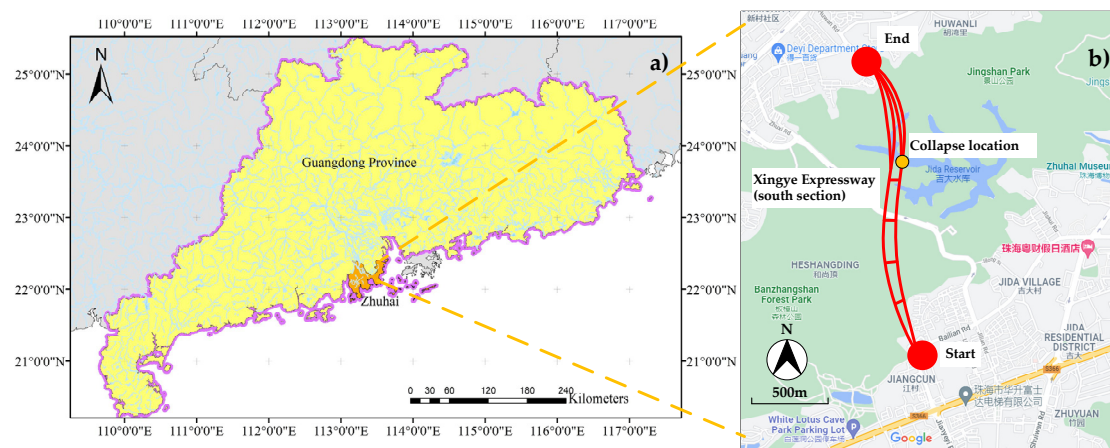


Figure 1. Location map of the collapsed tunnel: (a) map of water system, Guangdong Province; (b) accident tunnel due to inrushing in Zhuhai, Guangdong Province, on 15 July (map Google map).

3. Results

3.1. Water Inrush Accident

The water inrush accident occurred at 3:30 a.m. on 15 July resulting from an arch collapse of the east tunnel. Before the accident, the blasting work had finished in the east tunnel at 18:55 p.m. on 14 July. The following rock cleaning work continued for around 9 h until 2:35 a.m. on 15 July. However, no additional support systems were constructed except for the advanced support pipes without grouting. At 3:28 a.m., a large amount of sand and stone fell down from the arch. Two minutes later, the arch of the east tunnel without support completely collapsed with water bursting into the east tunnel. The water then rushed into the west tunnel through a linkage channel. Figure 2 shows zone water level in the tunnel after water inrush accident. Fourteen people were trapped in the west tunnel, 1160 m away from the portal (see Figure 2). According to the investigation, the direct cause of the accident is that when the tunnel passes through the Jida Reservoir, it encountered a deep weathered trough rich in water, and due to improper construction method and delayed supporting system, the arch of the east tunnel collapsed and flooded, which poured into the west line tunnel and caused the drowning of operators. The hydrogeological and tunnel results of the accident area were complex, resulting in the following rescue difficulties:

- The accident area with complex hydrogeological conditions is a hilly landform, and the main strata are granite and weathered soil. Fractures are developed in local granite. Huwan Fault and Jida fault are found in the surrounding area, which are affected by tunnel construction and flood accident. Affected by the surrounding faults and

secondary faults, the fracture development of rock mass in the accident area had reached a state of fragmentation.

- There is a strong hydraulic connection between the tunnel and Jida reservoir. The water level of the reservoir decreased by 1.9 m within 1.5 h since the occurrence of water inrush accident. An estimate of $2.2 \times 10^5 \text{ m}^3$ water flowed from the reservoir into the tunnels. Due to the enhanced hydraulic connection in the early stage, abundant water supply in the tunnel increased the difficulty of drainage in the tunnel. At the same time, influenced by tunnel construction and the flooding accident, the hydraulic connection between the Jida reservoir and the tunnel increased, and abundant water supply in the tunnel further increased the difficulty of drainage in the tunnel.
- The construction workers were trapped in the downhill section of the tunnel. The tunnel has a slope of 3%, so is not a straight tunnel. As the trapped personnel point was located in the downhill section, the slope of the tunnel lead to mud and sediment deposition, resulting in frogmen and underwater robots closer to the trapped point. The muddier the water, the more complex the rescue environment.

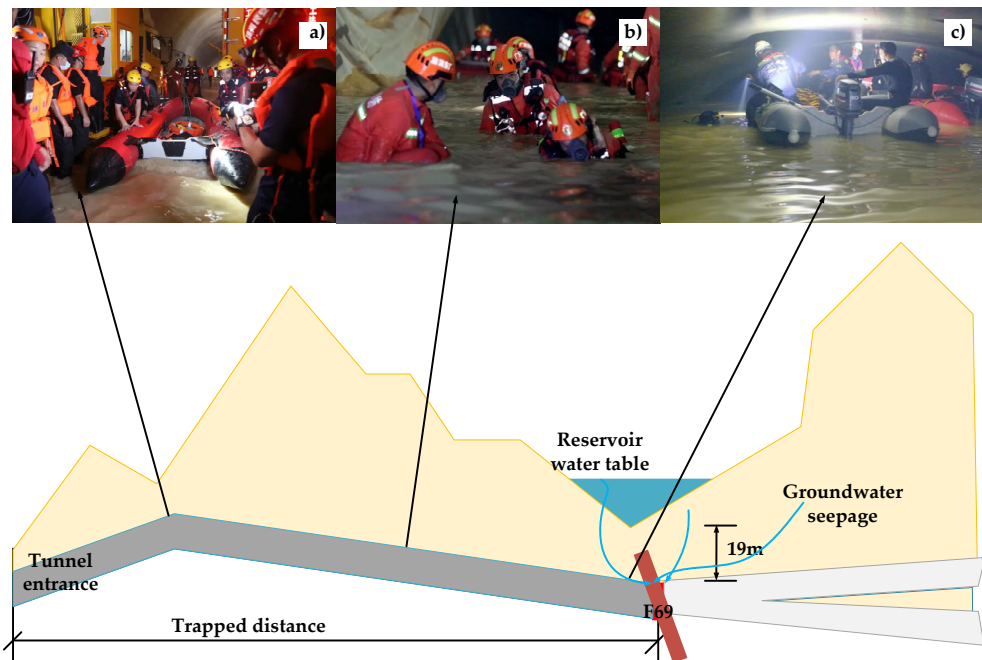


Figure 2. Zone water level in the tunnel after water inrush accident: (a) The transport port is at the lowest water level (https://www.guancha.cn/politics/2021_07_17_598831_s.shtml, accessed on 18 January 2022); (b) The water in the middle reached rescuers' waists (https://www.xianjichina.com/news/details_275025.html, accessed on 18 January 2022); (c) The highest water level for rescue, where oxygen is scarce (https://www.thepaper.cn/newsDetail_forward_13726501, accessed on 18 January 2022).

3.2. Rescue Operation

- In the upstream of the reservoir, a water barrier cofferdam was set to divide the reservoir into two parts, blocking the connection between the subsidence area and the water source of the reservoir, so that the external inflow of water into the tunnel was reduced from the original whole reservoir to a small pond. Then, the existing body of water above the tunnel collapse was drained. Through performing the above measures, the Jida reservoir surface water supply to the cave was prevented. Drainage equipment had been continuously increased, including 10 mud pumps, 7500 kW generators, 175 kW mixed-flow pump, 275 kW water pumps, 330 kW submersible pumps, 390 kW sewage pumps and 10 tank trucks. Pumping was also carried out inside the tunnel (see Figure 3). To solve the problem of excessive carbon monoxide

concentration in the tunnel, the rescue team added and started 8 jet fans on the basis of the existing 8 axial flow fans, which improved the rescue operation environment.



Figure 3. Rescue workers are laying out pumping equipment (Picture from: https://www.guancha.cn/politics/2021_07_17_598831_s.shtml, accessed on 18 January 2022).

- The rock was already broken, so strong grouting was needed during the rescue to ensure the safety of people at the rescue operation surface. After the water was drained, the soil was backfilled in the surface pit, and the mechanical equipment working face was created by leveling and compaction. Figure 4 depicts the rescue site of reservoir above tunnel. Then, the all-in-one machine drilled and fully spread, and the double-liquid grouting technology was adopted to reinforce the backfilled soil and the face of the tunnel. The double slurry can be solidified within 30 to 50 s, so that the backfill soil can be solidified and compacted quickly, subsequently, the original loose soil can be condensed into a compact and integrated structure, so it can effectively block the reservoir water and underground fissure water flowing into the tunnel. Twenty sets of equipment and more than 110 workers had been invested, and the backfilling of the vault was completed by 3 p.m. on 16 July, with around 11,000 square meters of soil. As of 9 a.m. on 17 July, 90 tons of cement and 20 tons of sodium silicate had been put into the site, 12 integrated drilling and injection machines had been put into operation, and 50 square meters of grouting had been completed.



Figure 4. Rescue site cofferdam construction (Picture from: https://www.guancha.cn/politics/2021_07_17_598831_s.shtml, accessed on 18 January 2022).

- Guangzhou Salvage Bureau of the Ministry of Transport had the primary goal of sparing no effort to save people, eight south China Sea salvage bureau divers, six Guangzhou salvage bureau divers and three rescue experts rushed to the scene to participate in the emergency rescue. As of 9 a.m. on the 19th, the bureau had sent four batches of divers for a total of 16 h of search and rescue in more than 900 m of tunnel waters. Figure 5 shows the divers launched search and rescue.



Figure 5. Rescuers are sending frogmen into the water. (Picture from: https://www.xianjichina.com/news/details_275025.html, accessed on 18 January 2022).

- Monitoring the tunnel structure safety and harmful gases in the cave. In order to prevent the occurrence of secondary disasters, the real-time monitoring of surface hydrology was constantly strengthened, especially the monitoring of mountain, reservoir, water body and surface backfill (see Figure 6). They monitored for tunnel leakage, ground subsidence and toxic and harmful gases in the cave and establishing a regular warning mechanism for the inside and outside of the cave every 30 min, to ensure the safety of rescue workers.



Figure 6. Emergency rescue and surveillance system on the right. (from: https://www.guancha.cn/politics/2021_07_17_598831_s.shtml, accessed on 18 January 2022).

Unfortunately, on 22 July 2021, after days of continuous search and rescue, all 14 trapped persons were confirmed dead.

4. Discussion

4.1. Geological Condition

The tunnel begins near Bailian Village and crosses the entire Banzhang Mountain Forest Park from the south to the north side. The Shijingshan Tunnel was excavated by using NATM, which is adopted when the geology is typically through very hard rock with MPa levels greater than 100. Hard rock tunneling commonly involves blasting, and hard rock is broken before excavation. Figure 7 shows the geological profile in the site. During the construction process of the Shijingshan Tunnel, weathered granite was the primary component of Banzhang Mountain (see Figure 7), the distance between the crown of the tunnel and the bottom of the reservoir is approximately 19 m, which constitutes a major risk source for the Shijingshan tunnel. Before the accident, because of a lack of bore holes, the ground was roughly estimated as moderately weathered granite, which had sufficient strength to support the upper ground load in the bench cut method. However, during the detailed geological investigation after the accident, the actual geological conditions around the water inrush area were discovered to be strongly weathered granite with developed fractures. The strength of rocks decayed significantly under groundwater. The bench cut method of NATM would have a potential risk of collapse in this case. The inaccurate estimation of geology is another reason of this accident.

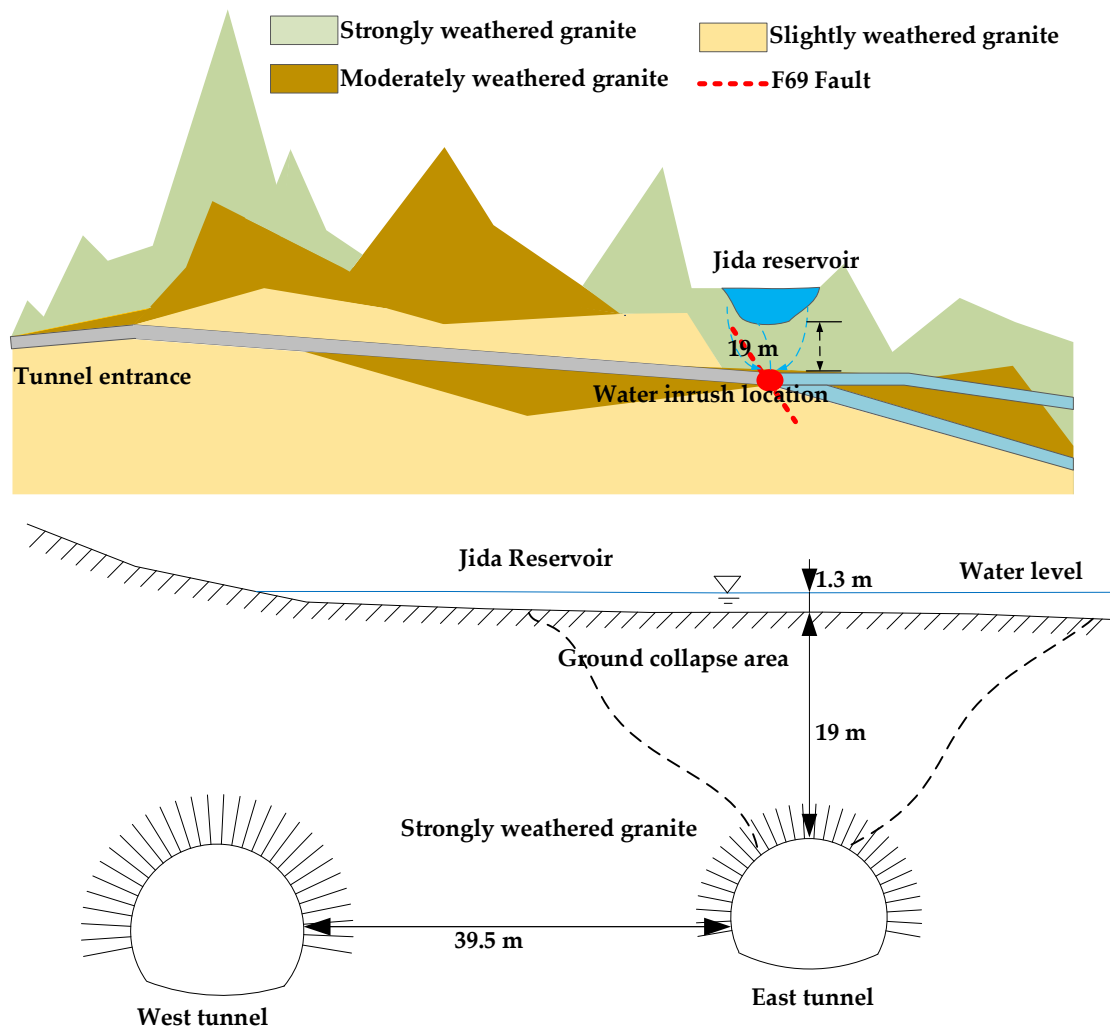


Figure 7. Geological profile in the site.

In hard rock tunneling, the blasting of hard rock can cause instability of the excavation face of the tunnel, even causing water inrush, which mostly occurs in the part where the rock

stratum contains fissures or faults. Figure 8 shows the intersection of Shijingshan tunnel and F69 is near Jida reservoir. The geological investigation before the construction of the Banzhangshan Tunnel revealed the existence of a fault crossing the Banzhang Mountains, which was referred to as the F69 fault based on the geological map of Zhuhai City (see Figure 8). This fault develops in the southwest-northeast direction. Considering the trend of this fault and the designed route of the Shijingshan Tunnel, there was a high probability that they may overlap around the site just underlying the Jida Reservoir. If this estimation was true, it would be the most dangerous area of the tunnel. Moreover, the reducing strength at the fault can intensify the instability of the excavation face of the tunnel. Consequently, if blasting excavation was undertaken without proper advanced support, the tunnel may collapse at any time owing to rock breakage.

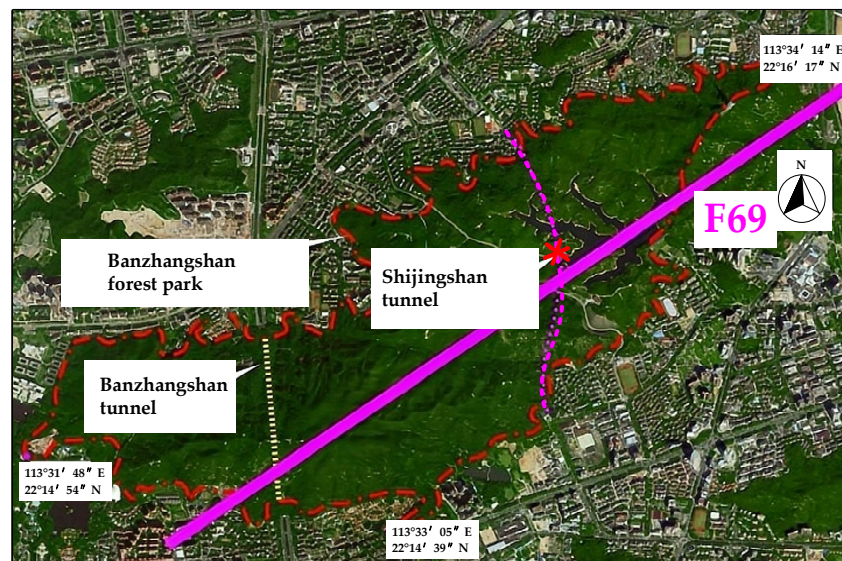


Figure 8. The intersection of Shijingshan tunnel and F69 is near Jida reservoir. (<https://zhuanlan.zhihu.com/p/390890982>, accessed on 18 January 2022).

As shown in Figure 7, the strata are composed of fill soil, gravel sand, fully weathered granite, strongly weathered granite, moderately weathered granite and slightly weathered granite. Among them, the filling soil is located at the top and is about 2–6 m in thickness. The recommended values of geotechnical parameters of the soil layer are listed in Table 1.

Table 1. Recommended values of geotechnical parameters of the soil layer.(the construction date from this project <https://www.doc88.com/p-19259446047410.html?r=1>, accessed on 18 May 2020).

Type	f_{a0} (kPa)	γ (kN/m ³)	w (%)	C (kPa)	ϕ (°)	E_{s1-2} (MPa)	E_0 (MPa)
Fill soil	90	18.3	25.0	22.0	15.1	4.15	
Gravel sand	170	18.1	12.6	-	41.7		
Fully weathered	300	19.0	22.5	21.2	25.4	5.02	118.5
Strongly weathered	600	-	-	-	-	-	234.6
Moderately weathered	1500			$f_{rk} = 24.85$ Mpa			
Slightly weathered	2800			$f_{rk} = 49.12$ Mpa			

Note: f_{a0} —Bearing capacity; γ —Natural gravity; w —Water content; E_{s1-2} —Compression modulus; E_0 —Deformation modulus; f_{rk} = Saturated uniaxial compressive strength.

4.2. Inrushing Mechanism

In this accident, the Jida Reservoir was the major risk source. The high hydraulic conductivity of the fault can result in such a water inrush accident. After the surrounding rocks collapsed, the water stored in the reservoir could quickly leak into the tunnel through the fault fracture zone, and finally induce a water inrushing accident. The maximum water level of Jida Reservoir could reach 20 m from the survey. The collapse of the excavation face at the east tunnel may form a “funnel” collapse cavity between the top of the tunnel and the bottom of the reservoir, resulting in the rapid flow of reservoir water into the tunnel as shown in Figure 7. The water would gush out of the right tunnel and flow into the left tunnel through the cross passage. Furthermore, the groundwater would continue to seep into the tunnel as well.

Since the water flowed directly from the reservoir into the tunnel, Darcy’s law of water seepage is suitable to estimate the actual permeability coefficient. Darcy’s law is expressed as follows.

$$Q = KA \frac{\Delta h}{L}$$

where, Q is the water inrush volume per unit time (m^3/s); K is the permeability coefficient of the ground (m/s); A is the area of water section (m^2); Δh is the water head difference (m); L is the length of seepage path (m).

In this case, the length of seepage path L is estimated as the minimum distance between the reservoir and tunnel of 19 m. The water head difference is assigned as the maximum values of 22.2 m. Then the maximum hydraulic gradient J is computed as $22.2/19 = 1.17$. During water rushing into the tunnel, the water level of the reservoir would decrease while the water level in the tunnel would increase. The water head difference would continue and thus would decrease. Due to the width of the nonsupport arch being 1.8 m, and the estimated circle is around 15 m, the area A is around 27 m^2 . According to the measured data in the field, the water reduced $2.2 \times 10^5 \text{ m}^3$ within 1.5 h, which means the average water inrush volume per second Q is around $40.7 \text{ m}^3/\text{s}$. Thus, the estimated permeability coefficient K in the field is $1.29 \text{ m}/\text{s}$. The actual permeability of $1.29 \text{ m}/\text{s}$ is far beyond the empirical values of weathered granite of $3.3 \times 10^{-6} \sim 5.2 \times 10^{-5} \text{ m}/\text{s}$ or gravel of $3 \times 10^{-4} \sim 3 \times 10^{-2} \text{ m}/\text{s}$. The excessive permeability coefficient of the ground confirmed the direct hydraulic connection between the reservoir and tunnel, which is a significant reason of this accident.

4.3. Heavy Rainfalls

Zhuhai is located south of the Tropic of Cancer, belonging to the subtropical maritime monsoon climate, abundant sunshine, abundant rainfall, often affected by the south subtropical monsoon and thunderstorms. The annual maximum precipitation was 2873.9 mm (1973), minimum precipitation was 1200.9 mm (1963), perennial average precipitation was 1950.7 mm, daily maximum precipitation was 393.7 mm (12 June 1966), the longest continuous rainfall days were 18, the rainfall was 378.3 mm (in July 1968). The annual distribution of rainfall was concentrated in summer, with 4–9 accounting for 80% [31]. Water sources due to rainfall were considered as another significant cause of the water inrush accident. The monthly average rainfall in Zhuhai reached its peak in July 2021. Moreover, there was continuous rainfall in Zhuhai on 7 July 2021 and it was also struck by a thunderstorm on 14 July 2021. Continuous rainfall is one of the critical triggering factors because it results in an increase in the water level of surface water and the upper reservoir, which is an important recharge source of the groundwater system. Consequently, the unfavorable situation was further aggravated because of the triggering factor of the continuous rainfall and tunnel excavation. Figure 9 shows a schematic cause-and-effect diagram of the water inrush accident.

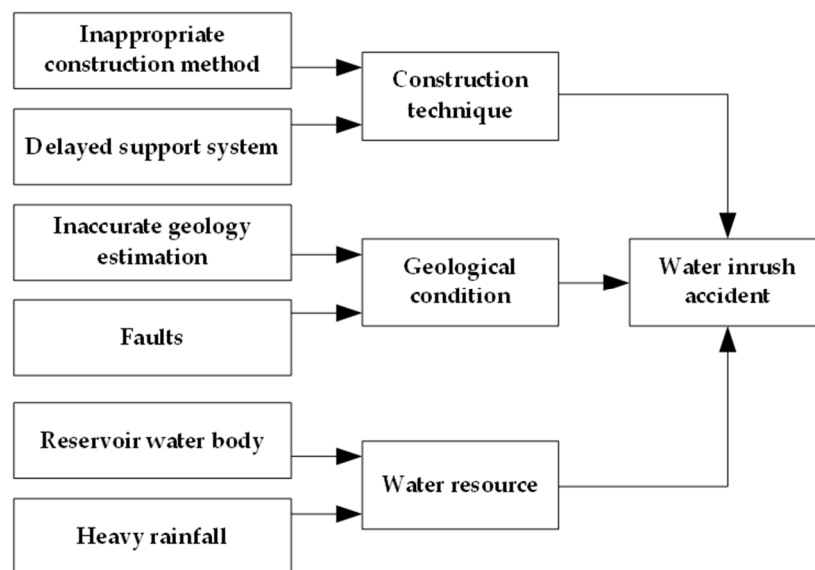


Figure 9. Triggering factors of water inrush accident.

5. Reflections

A tunnel is an optimal choice when designing railways or highways that pass-through mountain areas to shorten direct distances and avoid large ramps. However, many geohazards and fatal accidents have occurred during the tunneling process because of lack of sufficient knowledge on the geological conditions. For instance, two accidents have occurred in this unfavorable geological section of tunnel in 2021. These kinds of accidents have caused serious casualties and property loss in recent decades. The water inrush hazard in this communication is a catastrophic accident and is difficult to deal with. The geological condition and water source should be properly investigated to relieve the potential disasters.

- The development of water inrush is complicated, and it is difficult to acquire a comprehensive understanding on the mechanisms of water inrush. There exist some influencing factors which contribute the occurrence of water inrush, such as, stress change during tunneling, the development of rock fissure, the change of surrounding environment, etc. Due to the coupling effects of these mentioned factors, the traditional empirical methods are not suitable anymore. The artificial intelligent (AI) methods are potential techniques to handle situations where many influencing factors exist coupled together. A combination of geographical information systems (GIS) and AI have the potential ability to reveal the mechanism of water inrush during tunneling.
- It is necessary to have a clear survey on the engineering geology on the path of the tunnel to be constructed. The borehole method is commonly adopted in real practice. However, the construction workers have to balance the cost of drilling boreholes and the accuracy of engineering geology. Then, it is a challenging task to predict the variation of geology conditions based on limited borehole data. It is a good choice to combine the new arising techniques, such as transient electromagnetic technique and ground penetration radar method, with the traditional borehole method to obtain high fidelity prediction of geology conditions.
- It is crucial to establish monitoring systems to mitigate the damage caused by water inrush accidents. Reliable monitoring methods should be cost-effective and user friendly and they are convenient to be applied in complex geological conditions, such as karst geology. Nowadays, the new emerging fiber-based sensors are popular in geotechnical engineering, and they can efficiently measure the stress change, displacement, water pressure, etc. This type of technique is more suitable for tunneling projects that involve a number of influencing factors. Based on the collected data associated with an AI

algorithm, the monitoring center can provide instructions or give a warning when the situation becomes irregular.

- The partial application of shield construction can be considered. As a powerful temporary support structure, a shield can resist external water pressure and bottom pressure. The construction of long tunnels, which have a large buried depth in soft water-bearing stratum often have technical and economic advantages and fit the construction conditions of this project.

6. Concluding Remarks

This communication is on a water inrush hazard that occurred on 15 July 2021, in Zhuhai, Guangdong, China. Some conclusions were drawn as follows.

1. A catastrophic water inrush accident occurred at a tunnel construction site in Zhuhai City, this accident was located under a reservoir named Jida Reservoir, rendering rescue extremely difficult and resulting in 14 casualties.
2. The disaster was triggered by the coupling effects of: (i) high hydraulic conductivity of the surrounding soils at the construction site, (ii) faults formed around the construction site (F69), (iii) heavy rainfall prior to the accident and (iv) water source from the overlying reservoir.
3. It is necessary to conduct risk assessments in water inrush hazard-prone areas during tunneling. Effective in situ monitoring methods should be utilized to forecast possible human made disasters. Further, it is significant to investigate the geological condition along the path of tunneling using AI methods based on limited borehole data. An AI technique can assist in monitoring the occurrence of this kind of accident and enhance the rescue efficiency. For instance, AI techniques can monitor the water seepage point and the deformation of the excavation surface in the primary stage, and thus warn the manager for countermeasures. It can also track and identify survivors in the rescue process, which can save lives.

Author Contributions: Conceptualization, H.-Q.K. and N.Z.; formal analysis, H.-Q.K.; investigation, H.-Q.K. and L.-S.Z.; resources, H.-Q.K. and N.Z.; data curation, H.-Q.K.; writing—original draft preparation, H.-Q.K.; writing—review and editing, H.-Q.K. and N.Z.; visualization, L.-S.Z.; supervision, L.-S.Z.; funding acquisition, L.-S.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been supported by the National Natural Science Foundation of China (Grant No. 4210020169) and the Research Funding of Shantou University for New Faculty Member (Grant No. NTF21008-2021).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Lyu, H.M.; Shen, S.L.; Zhou, A.; Chen, K.L. Calculation of pressure on the shallow-buried twin-tunnel in layered strata. *Tunn. Undergr. Space Technol.* **2020**, *103*, 103465. [\[CrossRef\]](#)
2. Lin, S.S.; Shen, S.L.; Zhou, A.; Xu, Y.S. Risk assessment and management of excavation system based on fuzzy set theory and machine learning methods. *Autom. Constr.* **2021**, *122*, 103490. [\[CrossRef\]](#)
3. Lyu, H.M.; Zhou, W.H.; Shen, S.L.; Zhou, A. Inundation risk assessment of metro system using AHP and TFN-AHP in Shenzhen. *Sustain. Cities Soc.* **2020**, *56*, 102103. [\[CrossRef\]](#)
4. Lin, S.S.; Shen, S.L.; Zhou, A.; Xu, Y.S. Novel model for risk identification during karst excavation. *Reliab. Eng. Sys. Saf.* **2021**, *209*, 107435. [\[CrossRef\]](#)
5. Atangana Njock, P.G.; Shen, S.L.; Zhou, A.; Modoni, G. Artificial neural network optimized by differential evolution for predicting diameters of jet grouted columns. *J. Rock Mech. Geotech. Eng.* **2021**, *13*, 1500–1512. [\[CrossRef\]](#)
6. Chin, Y.T.; Chen, J. Foundation pit collapse on 8 June 2019 in Nanning, China: A brief report. *Safety* **2019**, *5*, 68. [\[CrossRef\]](#)

7. Yu, C.; Zhou, A.; Chen, J.; Arulrajah, A.; Horpibulsuk, S. Analysis of a tunnel failure caused by leakage of the shield tail seal system. *Undergr. Space* **2020**, *5*, 105–114. [[CrossRef](#)]
8. Shen, S.L.; Wu, H.N.; Cui, Y.J.; Yin, Z.Y. Long-term settlement behavior of metro tunnels in the soft deposits of Shanghai. *Tunn. Undergr. Space Technol.* **2014**, *40*, 309–323. [[CrossRef](#)]
9. Chai, J.C.; Shen, S.L.; Ding, W.Q.; Zhu, H.H.; Cater, J.P. Numerical investigation of the failure of a building in Shanghai, China. *Comput. Geotech.* **2014**, *55*, 482–493. [[CrossRef](#)]
10. Kardani, N.; Zhou, A.; Nazem, M.; Shen, S.L. Improved prediction of slope stability using a hybrid stacking ensemble method based on finite element analysis and field data. *J. Rock Mech. Geotech. Eng.* **2021**, *13*, 188–201. [[CrossRef](#)]
11. Zhang, N.; Zheng, Q.; Elbaz, K.; Xu, Y.S. Water Inrush Hazards in the Chaoyang Tunnel, Guizhou, China: A Preliminary Investigation. *Water* **2020**, *12*, 1083. [[CrossRef](#)]
12. Shen, S.L.; Lyu, H.M.; Zhou, A.; Lu, L.H.; Li, G.; Hu, B.B. Automatic control of groundwater balance to combat dewatering during construction of a metro system. *Autom. Constr.* **2021**, *123*, 103536. [[CrossRef](#)]
13. Xie, Z.F.; Shen, S.L.; Arulrajah, A.; Horpibulsuk, S. Environmentally sustainable groundwater control during dewatering with barriers: A case study in Shanghai. *Undergr. Space* **2020**, *6*, 12–23. [[CrossRef](#)]
14. Lyu, H.M.; Shen, S.L.; Yang, J.; Zhou, A. Risk assessment of earthquake-triggered geohazards surrounding Wenchuan, China. *Nat. Hazards Rev.* **2020**, *21*, 05020007. [[CrossRef](#)]
15. Zheng, H.; Wang, L.W. Analysis on the climatic characteristics and impact of Rainstorm in Zhuhai. *Guangdong Meteorol.* **2020**, *36*, 19–23.
16. Zheng, Q.; Lyu, H.M.; Zhou, A.; Shen, S.L. Risk assessment of geohazards along Cheng-Kun railway using fuzzy AHP incorporated into GIS. *Geomat. Nat. Hazards Risk* **2021**, *12*, 1508–1531. [[CrossRef](#)]
17. Lyu, H.M.; Shen, S.L.; Zhou, A.; Yang, J. Risk assessment of mega-city infrastructures related to land subsidence using improved trapezoidal FAHP. *Sci. Total Environ.* **2020**, *717*, 135310. [[CrossRef](#)] [[PubMed](#)]
18. Wu, H.N.; Shen, S.L.; Chen, R.P.; Zhou, A. Three-dimensional numerical modelling on localised leakage in segmental lining of shield tunnels. *Comput. Geotech.* **2020**, *122*, 103549. [[CrossRef](#)]
19. Lyu, H.M.; Sun, W.J.; Shen, S.L.; Zhou, A. Risk assessment using a new consulting process in fuzzy AHP. *J. Constr. Eng. Manag.* **2020**, *146*, 04019112. [[CrossRef](#)]
20. Elbaz, K.; Shen, S.L.; Zhou, A.; Yin, Z.Y.; Lyu, H.M. Prediction of disc cutter life during shield tunneling with AI via the incorporation of a genetic algorithm into a GMDH-type neural network. *Engineering* **2021**, *7*, 238–251. [[CrossRef](#)]
21. Lin, S.S.; Shen, S.L.; Zhou, A.; Xu, Y.S. Approach based on TOPSIS and Monte Carlo simulation methods to evaluate lake eutrophication levels. *Water Res.* **2020**, *187*, 116437. [[CrossRef](#)] [[PubMed](#)]
22. Yin, Z.Y.; Jin, Y.F.; Shen, J.S.; Hicher, P.Y. Optimization techniques for identifying soil parameters in geotechnical engineering: Comparative study and enhancement. *Numer. Anal. Methods Geomech.* **2018**, *42*, 70–94. [[CrossRef](#)]
23. Lyu, H.M.; Shen, S.L.; Zhou, A.N.; Yang, J. Perspectives for flood risk assessment and management for mega-city metro system. *Tunn. Undergr. Space Technol.* **2019**, *84*, 31–44. [[CrossRef](#)]
24. Wang, Z.F.; Shen, S.L.; Modoni, G.; Zhou, A. Excess pore water pressure caused by the installation of jet grouting columns in clay. *Comput. Geotech.* **2020**, *125*, 103667. [[CrossRef](#)]
25. Shen, S.L.; Wang, Z.F.; Cheng, W.C. Estimation of lateral displacement induced by jet grouting in clayey soils. *Geotech. ICE* **2017**, *67*, 621–630. [[CrossRef](#)]
26. Wang, Z.F.; Shen, S.L.; Modoni, G. Enhancing discharge of spoil to mitigate disturbance induced by horizontal jet grouting in clayey soil: Theoretical model and application. *Comput. Geotech.* **2019**, *111*, 222–228. [[CrossRef](#)]
27. Yan, T.; Shen, S.L.; Zhou, A.; Lyu, H.M. Construction efficiency during shield tunnelling in soft deposit of Tianjin. *Tunn. Undergr. Space Technol.* **2021**, *112*, 103917. [[CrossRef](#)]
28. Shen, S.L.; Atangana Njock, P.G.; Zhou, A.; Lyu, H.M. Dynamic prediction of jet grouted column diameter in soft soil using Bi-LSTM deep learning. *Acta Geotech.* **2021**, *16*, 303–315. [[CrossRef](#)]
29. Chen, J.H. Progress of Zhuhai Tunnel Flooding Accident: 14 People Trapped 1160 Meters Away from the Entrance. Available online: https://www.thepaper.cn/newsDetail_forward_13594591 (accessed on 15 July 2021).
30. Chai, M.Y. Cofferdam Has Been Used to Block the Permeable Point of the Tunnel Seepage Accident, and the Rescue Is in Progress. Available online: https://www.thepaper.cn/newsDetail_forward_13594373 (accessed on 15 July 2021).
31. Li, X.H.; Wang, D. Characteristics of precipitation of Zhuhai since 1962 to 2010. *Guangdong Meteorol.* **2012**, *34*, 35–37. [[CrossRef](#)]