Analysis and Handling of Water Inrush Accicidents in Leading Conduit Construction in Working Shafts

Linjun Qu[1], Hu Zhou[1], Hu Song[1], Wen Liu[2], Chengtao Xiang[3*], Shangang Wang[2]

[1]China Communications (Guangzhou) Construction Co., Ltd., Guangzhou 510030, Guangdong Province China;
[2]CCCC Wuhan Zhi Xing International Engineering Consulting Co., Ltd., Wuhan 430056, Hubei Province China;
[3]School of Civil and Hydraulic Engineering, Huazhong University of Science and Technology, Wuhan 430074, Hubei Province China

*xiangchengtaohust@163.com

Abstract. The construction of working shafts in shield tunneling projects is a challenging endeavor marked by deep excavation and intricate operations. It is further compounded by the frequent occurrence of water inrush accidents, particularly in regions where karst development is prevalent in the surrounding environment. These safety accidents during the construction of working shafts can have a cascading impact. They jeopardize the well-being of construction workers, pose threats to the lives and property of nearby residents, and disrupt the overall construction progress of the tunnel project. This paper is dedicated to a comprehensive analysis of the emergency response and monitoring strategies that come into play following a water inrush accident within a working shaft, with a specific emphasis on the context of constructing leading conduits in areas characterized by karst development. The specific content includes a technical analysis of the accident causes combined with geology and hydrology and the surrounding environment, and then formulating accident remedial measures and strengthening the monitoring of the surrounding environment in the whole process of emergency rescue, etc., and the monitoring results show that the risk of further expansion of the danger can be effectively solved by taking measures such as installing valves and drainage and grouting construction at the water inrush hole.

Keywords: working shaft; leading conduit; foundation pit; incidents; karst

1 Introduction

Over the 21st century, rapid urban expansion across China has led to increasingly dense city structures and a scarcity of surface space. This, in turn, has hastened the domestic development of underground spaces and advanced shield tunneling methods. Concurrently, the associated technologies for working shaft excavation and support have attracted widespread attention [1].

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Working shafts are critical for connecting shield tunnels to external environments, enabling the transport of machinery and construction materials, with their structural stability being paramount for the safety of shield tunnel construction [2]. At present, scholars at home and abroad have carried out a lot of research on the support and structural design of working well foundation pits, and the common support methods of working well foundation pits at this stage include enclosure piles, internal support and ground wall [3], among which the enclosure pile is a bored pile at the periphery of the foundation pit, which is suitable for foundation pits with a depth of less than 20m, but the overall stiffness is low; The inner support is suitable for large deep foundation pits, and the stability of the foundation pit structure is achieved by setting steel frame supports or reinforced concrete supports; The overall rigidity and strength of the ground wall are large, and it can withstand greater water and soil pressure. In the optimization and design of the supporting structure, numerical simulation is often adopted [4-6], and the rationality of the support scheme is determined by the simulation analysis of foundation pit deformation. When insufficient attention is paid to the investigation of the surrounding geological environment in the early stage of the project [7,8], or the design of the working well support scheme is unreasonable, accidents are easy to occur in the complex geological environment [9,10], such as the pipe surge accident of the working well of the Nanjing Weisan Road River Crossing Channel Project and the 7.25 collapse accident of Zhengzhou Metro.Mismanagement of such incidents can cause delays in construction and reduce economic outcomes, induce subsidence and deformation in nearby structures and pipelines, and pose safety risks to workers [11,12]. Therefore, investigating emergency response measures for construction incidents in working shafts emerges as a pivotal research area.

This paper investigates a water inrush accident in leading conduit construction in the shaft at small mileage. By considering the on-site conditions and geological circumstances, we found the causes of the incident, and promptly controlled the water inrush. Simultaneously, the frequency of monitoring was increased at surface settlement points, water level monitoring stations, and building monitoring points around the excavation pit to prevent further expansion of the water inrush.

2 Construction Overview

2.1 Project Overview

The working shaft, acting as both a launch shaft and reception shaft, has a circular excavation pit, an inner diameter of 34.6 m, an overburden of about 20.3 m on the top slab, and an excavation depth of approximately 34.1 m. The supporting structure incorporates an 800 mm thick diaphragm wall, two 1 m × 1 m ring beams, a 1.5 m × 1 m ring beam, and an inner wall. To adhere to the criteria for the launch shaft, a 20 m tunnel is arranged at the small mileage, and a 50 m trailing tunnel, implemented with a mining method, is placed at the large mileage. Geology and Hydrological Conditions

The stratigraphy within the pit, from the surface downward, encompasses plain fill, silty clay, mud, medium coarse sand, highly weathered siltstone, deposits in solution channel, moderately weathered limestone, and a dissolution fracture zone (Fig. 1).

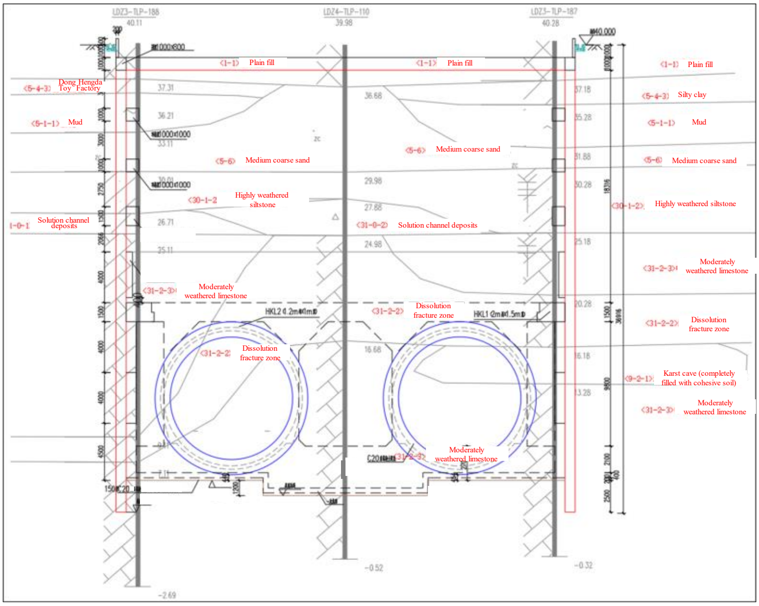

Fig. 1. Geological cross-section of working shaft

The working shaft is 380 m away from the Longxi River. Groundwater at the site is classified into three types based on geographic conditions: pore water in loose soils, fissure water in batholith, and karst water. Pore water is mostly found in the riverbank terraces and alluvial plains, primarily appearing as free-standing water and partially under slight pressure in some areas, supplied by rainfalls and surface water runoff. Fissure water mainly exists in the highly and moderately weathered zones of the rock, with vertical replenishment from the overlaying Quaternary layers. Karst water is typically found in limestone and marble, and with its surface largely covered by Quaternary loose deposits, it is confined and found in covered karst areas. The groundwater level closely relates to atmospheric precipitation; the upper phreatic water level peaks and troughs align with those of rainfall, with an annual water level fluctuation between 1.2 m and 3.5 m. The confined water level peaks about one month after the rainy season, with a minimal annual water level fluctuation, ranging from 0.5 m to 2.0 m. In areas near the surface water, the noticeable impact of groundwater replenishing surface water is evident.

2.2 Surrounding Buildings

The working shaft is situated west of Dong Hengda Toy Factory, at a distance of 43.24 m from the excavation pit, while to the east lies Baishi International Automobile City, with the closest building being 26.47 m from the pit.

The sudden water seepage influenced the pit and its support structures and affected the surrounding groundwater levels. However, impacts on the pit's inclination, pile displacement, and surface settlement were minimal, posing no threat to the pit's safety. The situation was brought under control following prompt reinforcement measures.

3 Incident and Management

3.1 Incident and Management

The left and right forepoling tunnels of the working shaft were each designed with 27 piles, encountering 7 and 10 instances of water inrush through the boreholes, respectively.

On the early morning of July 10, 2022, an unexpected water inrush was observed at the boreholes of the forepoling tunnels in the direction of small mileage on the right line. The project team promptly initiated emergency response actions. After progressively sealing leaks on the right line, a water inrush incident also occurred on the left line. Initially, the water influx was approximately 200 m3/h. The team applied grouting at the borehole entrance and surface and used pumps for water removal. By 13:00 on the same day, the water inrush was under control, and the pit's water level had visibly dropped. The maximum volume of accumulated water reached approximately 485 m3, with a depth of 50 cm.

3.2 Installation of Valves and Drainage

The primary measure involves sealing and draining the boreholes. A steel pipe, 1 m in length and 50 mm in diameter, equipped with a ball valve, is installed at where the water inrush happened. Quick-drying cement is used for sealing between the borehole wall and pipe wall, continuing until the leakage is completely controlled.

After sealing off the boreholes, water flow channels will form and create hydraulic pressures. Fully sealing these boreholes may lead to secondary water inrush or pose potential damage to vulnerable areas. Therefore, it is necessary to leave one hole unsealed to reduce the water pressure and prepare for grouting.

3.3 Grouting Works at Boreholes

On the ground, we set up cement mixing pipes and a storage area for sodium silicate. Then, we connect them to the boreholes using pipelines and grouting heads equipped with ball valves and perform dual-liquid grout treatment.

The water glass-to-cement ratio in the dual-liquid grout is 1:1, with the density of water glass to cement also at 1:1. Given the significant hydraulic pressure, achieving a thorough mixing of water glass and cement slurry is challenging. Therefore, the reaction time for both components is adjusted to approximately 20 seconds, and continuous grouting is performed until the water inrush ceases.

3.4 Ground Grouting

Simultaneously with underground grouting, grouting at the surface is performed using integrated drilling equipment. The focus is on the water inrush point, where grouting is executed at positions 1 meter to the left, front, and right. The sequence follows left, front, and right holes (as shown in Fig. 2). Drilling reaches a depth of 27 meters, extending 1.2 meters below the diaphragm wall. The grout mixture matches that specified in Section 3.2, with a setting time of approximately 27 seconds. Grouting begins incrementally from the hole bottom, and when the grouting pressure reaches 1 MPa, it stabilizes for 10 minutes. After raising the grouting pipe by 1 meter, grouting continues, resulting in a total grouting length of 13 meters.

If sealing the water inrush point at these three locations proves unfeasible, additional rows of grout holes are placed 6 meters and 7 meters from the pit's edge. Five geological drilling machines are deployed simultaneously for drilling. These two rows of drilling holes are arranged with a longitudinal spacing of 1 meter and a lateral spacing of 2 meters, totaling 55 holes. Sleeve valve pipes are used for grout injection, forming a water-stop curtain. Drilling reaches a depth of 37.5 meters, with a grouting depth of 23.5 meters, and the grout mixture remains consistent with the specifications in Section 3.2. The grouting process begins at the water inrush points and expands outward on both sides until sealing the water inrush points.

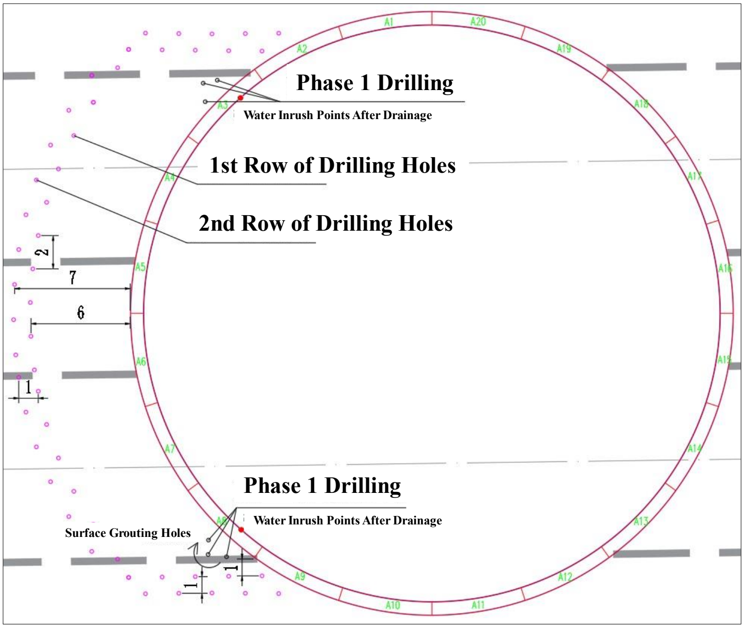

Fig. 2. Layout of ground drilling

Up to 7:00 AM on July 12, 2022, ten ball valves have been installed in the right line, and all of them have undergone grouting treatment. The phase 1 drilling at the surface and grouting is now complete, effectively stopping any further water inrush.

For the left line, seven ball valves have been fitted at the water inrush points in forepoling tubes. Concurrently, quick-drying cement has been used to seal off other tubes, channeling the water inrush points to a single location for surface drilling and grouting. By 3:00 AM on July 13, all water inrush points had been completely sealed.

4 Analysis of Causes of the Incident

- Prior to the forepoling process at the small mileage, the geological and hydrological conditions in the surrounding area were not investigated, and adverse geological phenomena were not addressed. During the construction process, the side wall of a water channel was inadvertently pierced, leading to the occurrence of the water inrush incident, which is the primary cause of the accident.
- Project management did not give sufficient attention to water leakage. When minor seepage occurred, effective measures were not promptly taken. This resulted in an increase in the later water inrush volume, causing water inrush to the excavation pit.
- Construction workers lacked experience in managing water inrush incidents, and during the grouting process of the sleeve valve pipe, they did not use casing materials as required. This hindered the progress of sealing water inrush points in the excavation pit.
- Staff at the construction site did not prioritize the collection and organization of geological, hydrological, and structural data in the vicinity of the work well. Consequently, when the incident occurred, relevant data could not be promptly accessed for analysis and handling.

5 Monitoring

To ensure the safety and stability of the excavation pit and the surrounding infrastructure during shaft construction, as well as to promptly detect and report any changes in the surrounding area, we conduct monitoring of key factors. These include groundwater levels, surface settlement, building settlement, and pipeline settlement within and around the excavation pit. This monitoring serves as the basis for assessing the impact and managing potential accidents. The locations of monitoring points in the vicinity are illustrated in Fig. 3. Following the water inrush incident, the monitoring frequency has been increased to every 2 hours.

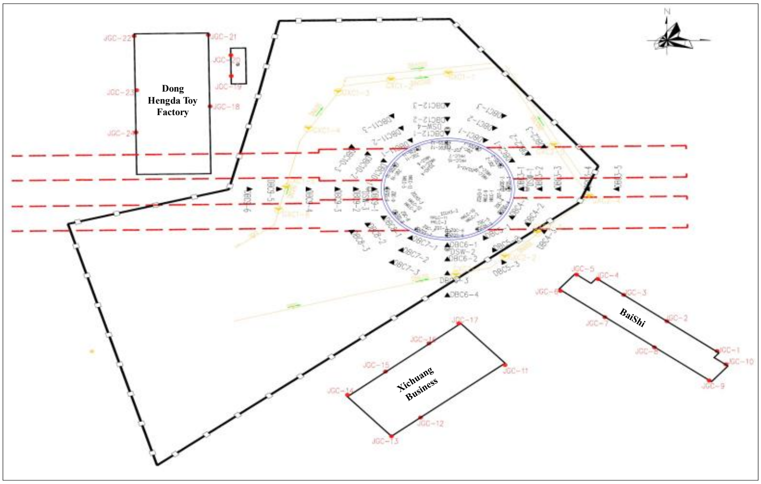

Fig. 3. ayout diagram of monitoring points

5.1 Monitoring During Emergency Response

During the emergency response phase, a water inrush incident occurred in the excavation pit of the work well during the early hours of July 10. The water inrush was gradually brought under control by 13:00 on the same day. As depicted in Fig. 4, there was a significant decline in groundwater levels from the 9th to the 10th, with the maximum decrease measuring 2,221 mm. Importantly, all monitoring points exceeded their warning thresholds. Between the 11th and 13th of July, groundwater levels displayed minimal fluctuations and indicated a trend of rebounding. This effective management of water inrush in the excavation pit demonstrated clear results in the emergency response efforts.

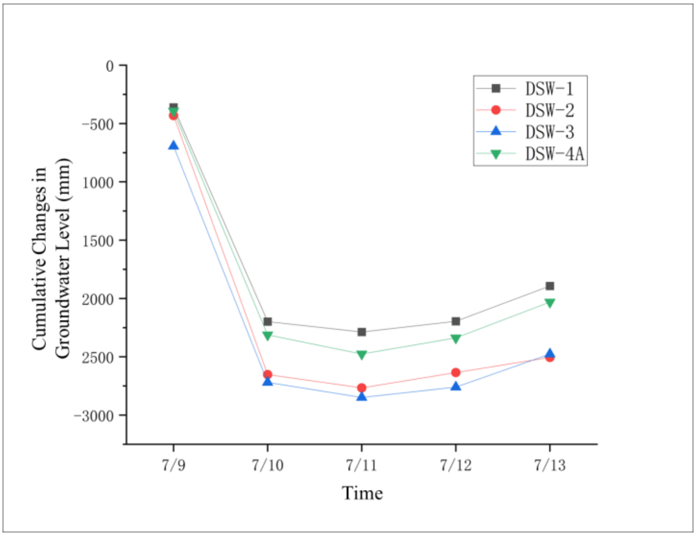

Fig.4. Variation curve of groundwater level

As depicted in Fig. 5, between the 9th and the 10th, there were notable variations in surface settlement at a few monitoring points. Specifically, two monitoring points recorded settlement changes that exceeded the predefined warning thresholds. Following the emergency response measures, surface settlement in the subsequent days remained within the warning thresholds, and the cumulative settlement values did not surpass the control limits.

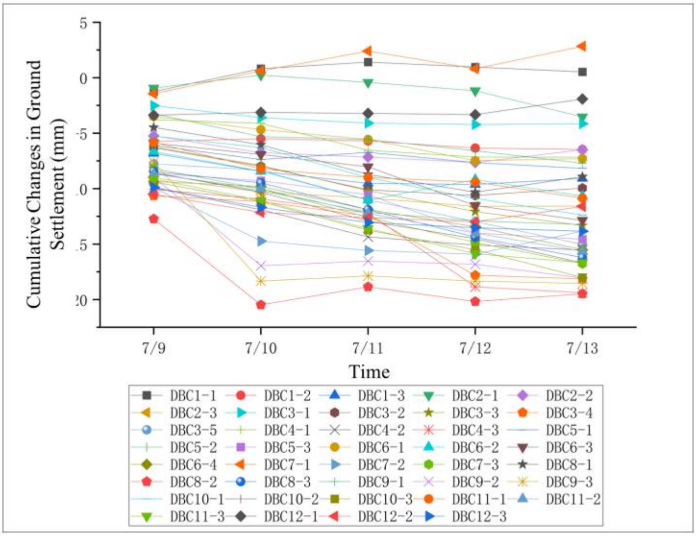

Fig. 5. Change curve of cumulative ground settlement in the surrounding area

Between the 9th and the 13th, the settlement rates of buildings surrounding the working shaft remained below the warning thresholds, and the overall settlement did not exceed the control limits, as depicted in Fig. 6.

The overall trend in pipeline settlement changes displayed a downward pattern (Fig. 7). Notably, significant settlement occurred on the 11th and 12th, surpassing the warning thresholds. On the 13th, cumulative displacement at two locations, GXC1-3 and GXC1-4, exceeded the control limits.

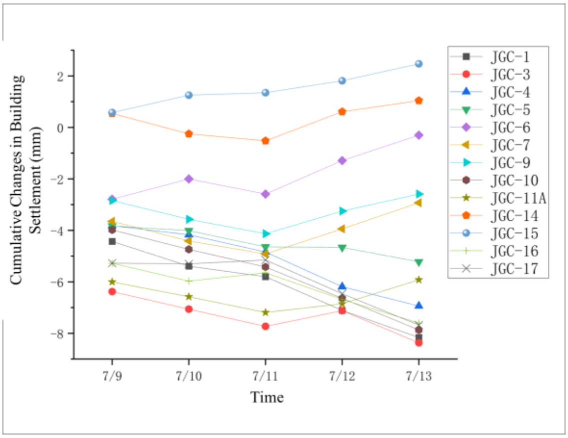

Fig. 6. Change curve in building settlement

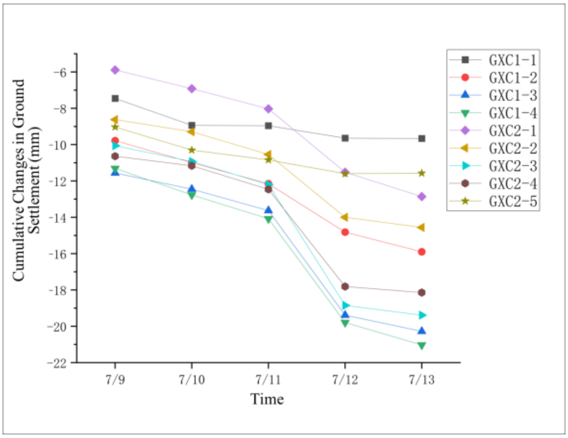

Fig. 7. Change curve of pipeline settlement

5.2 Monitoring After Sealing Water Inrush Points

After sealing water inrush points in the excavation pit, continuous monitoring was carried out for both the work well and its surrounding area. The following data represents the monitoring results from July 17 to July 22.

As illustrated in Fig. 8, the changes in groundwater levels around the working shaft during this period (from the 17th to the 22nd) exhibited minimal fluctuations and remained below the predefined warning thresholds. The cumulative changes in groundwater level closely resembled that observed during the emergency response phase, staying within manageable limits.

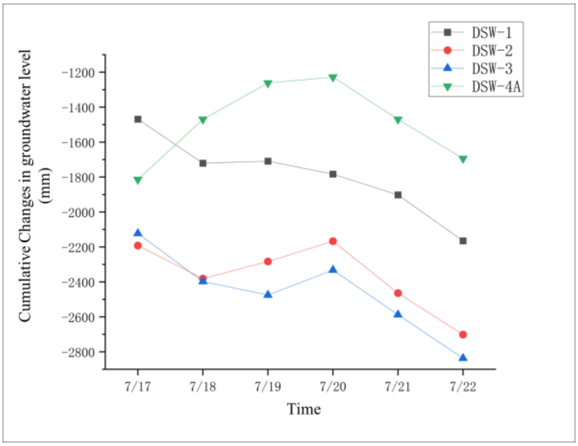

Fig. 8. Change curve of groundwater level

The settlement rates of the surrounding surface, buildings, and pipelines did not surpass the warning thresholds (Figs. 9, 10 and 11), and the cumulative settlement curves remained stable. However, at four monitoring points—GXC1-3, GXC1-4, GXC2-3, and GXC2-4—the cumulative values of pipeline settlement exceeded the established limits. Compared to the instances of exceeding limits observed on the 13th, the number of points exceeding the limits has increased, indicating the necessity for further monitoring.

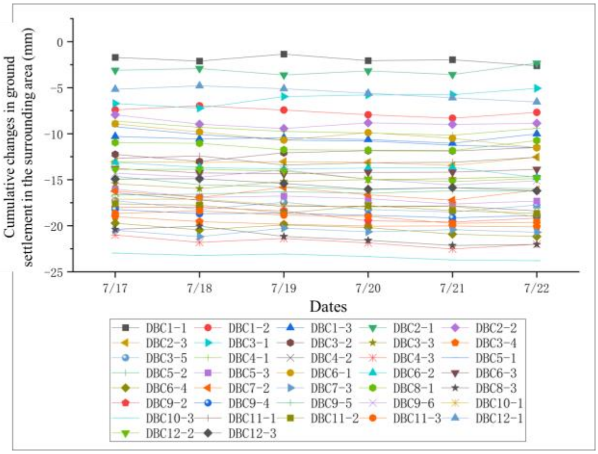

Fig.9. Change curve of cumulative ground settlement in the surrounding area

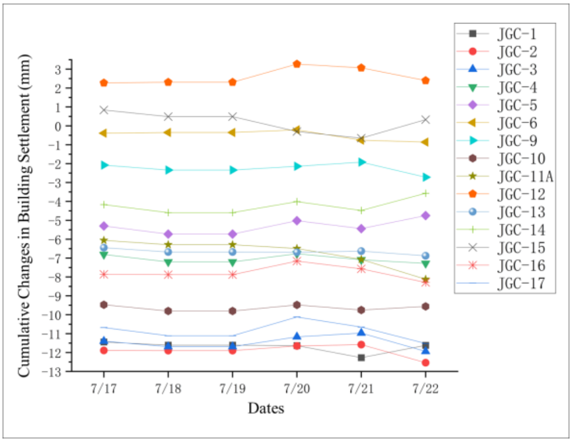

Fig. 10. Change curve of cumulative building settlement

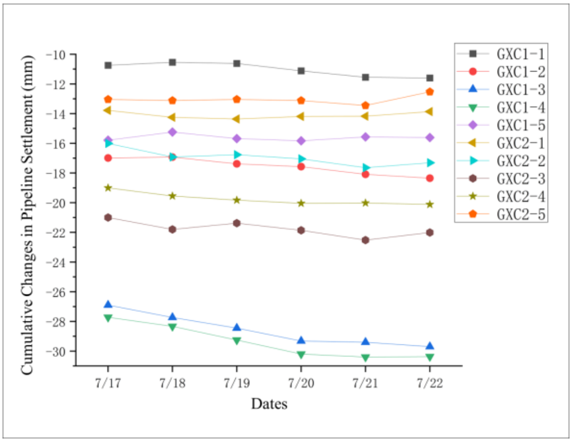

Fig. 11. Change curve of cumulative pipeline settlement

The water inrush incident influences the surrounding environment and facilities of the excavation pit. However, it did not pose a safety threat to the excavation pit itself. Monitoring data reveals that the water inrush in the excavation pit had a noticeable impact on the surrounding water levels. Still, its influence on nearby structures and surface settlement remained limited. Thanks to timely waterproof reinforcement measures, the excavation pit of the working shaft is currently in a secure and manageable state.

Once the water inrush is controlled, the forepoling process also ceases. Ground-penetrating radar was employed to investigate cavities around the excavation pit, and appropriate measures were taken to address karst formations in the affected areas of the excavation pit and the front and rear tunnels [13]. Construction of the mining method tunnels will proceed after successful treatment.

6 Conclusions

In deep excavation pits and tunnel excavation projects with significant karst formations nearby, the risk of accidental breaches of unknown karst sidewalls leading to water inrush accidents is significant. Therefore, accident prevention measures and corresponding emergency response actions are essential.

- Shaft construction of a shield tunnel requires deep excavation. Given the complex geological conditions in such projects, engineering survey data often falls short of fully representing the actual geotechnical conditions. Therefore, it is imperative to conduct comprehensive investigations and assessments of the hydrogeological conditions before starting construction. This process involves analyzing the likelihood of various risks and ensuring that sufficient emergency materials are readily available at the construction site to mitigate potential harm resulting from accidents.
- Prior to the forepoling process, advanced geological drilling techniques should be employed to detect the geological and hydrological conditions ahead of the cutterhead. This approach allows for early identification and mitigation of adverse geological phenomena, thereby preventing water inrush and other potential hazards.
- It is crucial to enforce safety education for all on-site workers to enhance their awareness of safe working practices. In the event of any abnormal situations during construction, immediate reporting and resolution are imperative. Construction activities must not continue in the presence of unresolved risks.
- Following an incident, it is necessary to increase the frequency of monitoring the surrounding environments of the excavation pit and expand the area covered by ground inspections. When abnormal values are detected, it is significant to promptly gather relevant technical experts for discussions and analysis, and take immediate measures to prevent the affected area from expanding further. Additionally, monitoring data plays a critical role in assessing how well the response measures to the incident have worked.

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