On the genesis of karst in red beds and underground engineer risks analysis

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Abstract: Red beds are a series of red or dark-red clastic rocks that have been deposited in continental basins under dry climate conditions since the Mesozoic. Long-term investigation and research have found that karst caves in red beds mainly develop as formations composed of coarse-grained clastic rocks in the periphery of the basin. When combined with the overlying water-rich loose soil, these formations pose a significant risk to underground projects. The present study systematically analyzes several large-scale engineering implementations in the red bed layer, reveals the development characteristics of karst caves in red beds, and discusses the relevant causes (or mechanisms) of karst formation, which include the long-term effects of abundant soluble debris, tectonic fissures, and paleochannel systems. The characteristics of underground engineering methods, such as pile foundations, foundation pits, and underground tunnels, were evaluated to determine the main risks causing ground collapse and structural damage, such as water inrush, mud bursting, and slurry leakage. Risk models for different construction methods were finally established.

Keywords: red beds, karst caves, underground engineering, engineering risk

1. Introduction

Academic research on red beds in China can be traced back to notable scholars such as Li Xihuofen in the 1860s–1870s and Chen Guoda and Zeng Zhaoxuan in the first half of the 20th century. Investigations of natural outcrops have led to discussions on the origins of red beds from the perspective of structural geology and geomorphology. After the People’s Republic of China was founded, the demand for infrastructure construction and mining engineering, as well as explorations of red beds, greatly increased. The formation of red beds has been studied intensively, and the development mechanism of karst in red beds has been discussed extensively. For example, Liu Shangren¹ and Liu Gongyu² summarized the strata on which karst develop, including calcareous and limestone conglomerates. Feng Qiyan and Han Baoping³⁴ revealed that red beds contain only small amounts of water. Zheng Xiaozhan, Yin Xin, Xiao Pan, and Jia Long⁵, 6, 7 also contributed work related to disaster geology. Jia Long pointed out that the collapse mode of red beds could be categorized as overburden layer collapse, red bed cave roof collapse, or whole red bed collapse. Xiao Pan indicated that karst ground collapses primarily occur through underground and vacuum suction.
erosion. The results above lay a solid foundation for research in engineering geology. However, studies on the correlation between red bed karst and underground engineering risk is lacking.

Since the construction of the Guangzhou Metro in 1965, over 300 kilometers of tunnels and stations have been excavated in red beds, more intuitive and larger-scale witness to the engineering geological features of the red bed, red bed karst, as well as the combination of red bed karst and overlying Quaternary loose strata, it can provide a basis for perfecting the “red layer karst genesis theory.” This paper analyzes the underground engineering risks or potential causes of accidents during construction in red bed karst development areas.

2. Red bed karst development conditions and evolution model

2.1. Karst development conditions

The process of karst development in red beds is nearly identical to that in limestone and includes three necessary conditions: (1) soluble rock or debris for cementation, (2) water for dissolution and transportation, and (3) structural fissures or faults to create hydraulic channels. Karst development could be described on the basis of three aspects as follows.

1. Material basis: Rich soluble limestone debris (or calcareous cementation)

According to the lithology analysis of the debris and upper and lower floors of large-scale karst caves in Guangdong, Guangxi, Shandong, and other locations, most of the dissolved rock is lime breccia (Figure 1). The composition of lime breccia exceeds 50%, and its rock mass is lenticular (Figure 2) with some three-dimensional extensions. It can be seen that it is a near-source foothill accumulation and alluvial deposit, and adjacent areas have gray parent rocks, such as limestone and dolomite in Carboniferous-Permian, etc. Fine-grained silty calcareous cemented rock layers, such as silty sandstone, could also be found in these caves but their volume or scale is very small (Figure 3).

2. Structural basis: Faults or fissures

Red beds generally show a shallow overburden, are easily weathered, and feature large changes in layer thickness. The mechanical characteristics of rocks in the Cenozoic include low strength and brittleness. Although the orogenic activity was strong and faults were well developed during this period, the folds were not developed and a large number of faults divided the red bed into several areas or blocks, which were eventually weathered to form “DanXia” landforms with several gullies alternating with domes. The size of a block is related to the rock lithology. Compared with mudstone, gray breccia is more likely to develop structural fissures, which could result in channels through which surface and groundwater enter and dissolve lime breccia.

3. Dynamic foundation: Groundwater and surface water system development

Water could dissolve the rock structure of limestone and its debris and carry the dissolved material away. Red bed karst developed after long-term water dissolution and transportation. In geological theory, all types of groundwater, such as karst water, fissure water, and surface water, could be considered dissolution media, but groundwater must be supplemented by surface water. Therefore, the development of surface water systems is a necessary condition for karst development. This condition
could explain why karst is mostly distributed in warm, tropical, and rainy areas. The presence of loose sand and gravel layers in the overlying stratum confirms the development of karst from surface water systems or ancient rivers. For example, numerous red bed karst development areas could be observed in several locations in Guangzhou, such as Datansha Island, Zhongluotan in Baiyun District, and Shahe in Tianhe District. Each these areas is characterized by thick channels with sedimentary sand and gravel layers above the red beds, thus confirming that the development of karst is closely related to the development of ancient rivers or water systems.

2.2. Karst evolution model
The factors influencing karst development in red beds were analyzed and the sedimentary environment and chronostratigraphy of the red bed were studied by taking the geological section from Hesha to Huangcun as an example. The evolution model of red beds from sedimentary diagenesis to red bed karst development could be summarized and divided into three stages.

First stage: Yanshanian to early Himalayan. Piedmont and alluvial deposits in the rifted basin formed red beds. Gray breccia mainly formed in the Piedmont facies of the neighboring soluble parent rock (Figure 4).

Second stage: Himalayan. Fault fissures developed in the basin and formed landforms between blocks, ravines, and domes (Figure 5).

Third stage: Quaternary Holocene. At the end of the glacial period, the climate was warm, the surface water system was well developed, and the sea level rose by 2–4 times (the average sea level rise of the Pearl River Delta is 30–40 m). Finally, the red bed karst cave was formed (Figure 6).
3. Risk analysis of underground engineering of red bed karst

Engineering risks in red bed karst can be divided into natural and man-made risks. Natural risks include earthquakes, storms, and seasonal changes in groundwater level, among others, and cause the collapse of karst caves. Man-made risks include surface loading, underground engineering, and other active triggers of karst caves causing water inrush, mud inrush, slurry leakage, and eventual collapse. This paper analyzes the engineering risks corresponding to various construction methods through accident cases.

3.1. Water and mud inrush during foundation pit excavation: Guangzhou Metro Line 6 Hesha Station

1. Incident overview

Hesha Station is located on Datansha Island, Liwan District, Guangzhou, which belongs to the Pearl River alluvial plain and is surrounded in three directions by a river. The station structure is built two stories underground, and its enclosure structure is an 800 mm diaphragm wall constructed 24–25 m deep. The burial depth of the structural floor is 14.5 m, and the surrounding environment is critical.

During the construction of the last section of the bottom plate, a large amount of confined water gushed out of the bedrock under the bottom plate (100 m³/h). Because the surrounding environment did not immediately show subsidence due to water inrush, construction of the foundation pit was not stopped. However, after some time, houses, transformers, and fish ponds near the foundation pit collapsed successively. The drainage ditch outside the diaphragm wall on the eastern side of the north end of the station also collapsed after water gushing. Eventually, the enforced drainage of the foundation pit had to be stopped, and the foundation pit was refilled with water. A hole (35 m deep) was drilled outside the diaphragm wall to block the main gushing channel. As the level of water recharging the foundation pit rose, the surrounding settlement began to stabilize. Afterward, zone grouting was used for plugging and the water in the foundation pit was drained out. Construction of the last floor was then continued.

2. Analysis of the cause of the accident

1) Geological factors. Undetected karst caves were present in the red bed excavated at the bottom of the foundation pit. The northern end of HeSha Station is in the development zone of fractured fissures, and soluble lime breccia covered with sand deposits from the ancient Pearl River system is present in this area. The conditions for the development of red bed karst caves described earlier indicate that karst caves may exist in the red bed, but this point was not mentioned in the preliminary and detailed survey reports. In fact, only the supplementary survey report created after the accident mentioned the possibility of these caves. Eleven drill holes revealed the presence of a karst cave in this area.

2) No awareness of the existence of karst caves. The design of the enclosure structure did not
3) No awareness that water inrush could cause subsequent collapse, and emergency measures, including water recharging, were immediately implemented.

3.2. Collapse of a mining platform tunnel: Guangzhou Metro Line 11 Shahe Station

1. Incident overview

Drilling engineering works were not completely implemented due to various reasons. While the geological conditions were not clear, it was designed as an underground excavated station, through the shaft and transverse passage (Figure 7). The transverse passage of this station is close to the Shahe River, with less than 10 m of the closest. On the northern side, approximately 1.0 km away, is the east-west Shougouling fault zone. The transverse passage was located in the red bed, and the average and minimum thicknesses of the rock layer on top of the tunnel were greater than 10 m and at least 8 m, respectively.

At 8:20 am on December 1, 2019, water inrush and slag spraying occurred at the excavation surface of the transverse passage. At 9:28 am, yellow muddy water, sand, and slag collapsed and poured into the shaft. The intersection of North Guangzhou Avenue and YuDong West Road suddenly collapsed; a sewage truck (2 persons) and an electric bicycle (1 person) passing through this section also fell into the pit. After the initial collapse, the size of collapsed area expanded several times over 4 hours, eventually measuring 570 m². The foundation pit was excavated downward at the site of the collapse, and clear excavate from the shaft to the transverse passage at the same time to enable the rescue of lost vehicles and civilians. When the foundation pit was excavated to a depth of 15 m, a cave was found in the rock layer. The collapse profile is shown in Figure 8.

2. Analysis of the cause of the accident

1) Geological factors. Undiscovered karst caves were present in the excavated red bed. The project was located in an area where fractures and fissures had developed (Figure 9; the excavation face rock layer is obviously staggered). The excavated stratum was meso-weathered sandy conglomerate partly...
lenticular breccia. Overlying this area were sand layers deposited by river bed facies. In fact, during construction on October 4, a hole was found in the excavation face. The supplementary survey report after the accident was processed, and nine drill holes revealed a karst cave.

2) Construction factors: No optimized blasting construction plan was available. Initial support was not immediately available, and the final steel arch and hanging net had not been erected after the second day of blasting. Emergency measures were not quickly implemented. The ground of the collapse was not surrounded in time and the shaft was not backfilled in a timely manner; thus, the water-rich sand layer moved to the shaft and secondary accidents of ground settlement occurred after December 3.

3.3. Shield engineering risks
The risk of shield tunneling through red bed karst is smaller than that of mining, pile foundation, foundation pit excavation, and other construction methods. The probability of an accident occurring in this case is small, and the degree of loss is low. This is mainly due to the function of shield machine. As long as an awareness of the presence of red bed karst is in place, shield construction parameters and measures could be adjusted in a timely manner and the corresponding risk could be generally controlled. Long-term shield tail leakage (Figure 9) and inadequate earth pressure control could also cause the sinking of nearby ground structures and environmental pollution (Figure 10).

4. Underground engineering risk (accident) model in red bed karst
A risk model of underground engineering in red bed karst could be established according to the cause mechanisms and engineering case analyses described above (Figure 11).
5. Engineering recommendations

1. The distribution law of red bed karst and its engineering geological conditions should be accurately recognized.

   Accurate recognition of the surrounding geology is the basis for controlling underground engineering risks. About the red bed karst, according to the three elements of its development: structural fracture zone, limestone parent rock, sand deposited by ancient channel, delimit the red bed karst high development area, medium development area, and low development area. In terms of zoning, standards for exploring and identifying karst caves could be supplemented and improved according to test holes.

2. Red beds karst should be pre-treated.

   Although the scale of karst caves in red beds is not especially large, the unforeseen risk probability is high during project implementation. Therefore, pre-grouting is necessary and the most effective choice.

3. Construction designs should be dynamically optimized according to different construction methods.

   ① Pile foundation or drilling construction: Drilling rig platforms in high red bed karst development areas should be provided with measures to prevent collapse, and the steel sleeve or drilling rig casing should penetrate into the stable rock layer.

   ② Foundation pit excavation: Measures should be taken to seal leaks during excavation in a timely manner. If these leaks are not plugged immediately, water inrush points could be suppressed or water could be recharged into foundation pits to balance the water and soil pressure inside and outside these pits and prevent surrounding subsidence.

   ③ Mining method: A certain number of long-distance horizontal drilling rigs should be arranged prior to excavation to understand the geological conditions and optimize the blasting plan, especially in terms of the blasting charge and initial support plan, according to changes in geology. Strict implementation of the “18-character policy” of the mining method during construction: pipe advance,
grouting strictly, excavate shortly, strong support, closure fastly, measure frequently.

④ Shield construction: Changes in the slag sample should be analyzed ring by ring, and the construction parameters should be paid attention to and adjusted as necessary to balance the pressure of the soil bin dynamically.

4. Construction process management should be implemented.
  ① Monitoring and control plans should be scientifically formulated to realize information construction according to the project and risk assessment results of the surrounding environment.
  ② Operations should be strictly implemented according to drawings and regulations.
  ③ Emergency plans should be developed, emergency supplies and equipment should be prepared, and emergency drills should be conducted often.

6. Conclusion
A model of karst development and evolution was established by analyzing the causes of karst cave development in red beds, accidents of underground engineering were discussed, and a risk (accident) model of underground projects in the red bed karst was established. The following conclusions were obtained:

1. Karst caves in red beds are often undetected during engineering and preliminary surveys. The causes of the development of karst caves in the red bed indicate that the coarse-grained debris in the latter is soluble lime breccia and that rock fissures are well developed. Sand and gravel layers in the river facies were deposited in the upper part of the ground. Attention must be paid to the detection of karst caves during detailed and supplementary surveys. However, it is not enough to judge the karst cave according to whether it is leaking water or dropping the drill. It should also be combined with analyses of the geotechnical composition and strength of the soil.

2. According to the underground engineering risk (accident) model of red bed karst caves, the main risks of underground engineering in red bed karst strata include water inrush, slurry leakage, and collapse. Among them, the mine method has a high risk probability of collapse, and the impact range of collapse is the largest.

3. Four measures should be taken to mitigate the underground engineering risks of red bed karst: ① Cognitive geology, that is, find karst caves; ② pre-treatment of earth and karst caves; ③ dynamic optimization of the construction design according to the features of various construction methods; and ④ preparation of a good risk assessment, monitoring, and contingency plan.

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