An Applied Study On Safety Warning Distance With Numerical Simulation For The Development And Management Of Subway Tunnels In Karst Area

Yongyao Wei12, Bing Hang3
(1.Geological Survey of Jiangsu Province, Nanjing 210049,China;2.Key laboratory of Earth Fissures and Geological Disaster Ministry of Land and Resources, Nanjing 210049,China; 3. Nanjing Xiaozhuang College, Nanjing 210098,China)

corresponding author: Bing Hang  email: 1572083371@qq.com

Abstract: If lacking scientific and rational planning and management when underground engineering is developed karst collapse risk area, it will bring immeasurable losses to subway construction, operation and disaster relief. To this end, this paper puts forward the concept of “Safety Warning Distance”. According to the final collapse form of karst soil cave-funnel-shaped collapse influence area, the critical slope angle $\beta$ is proposed in the subway tunnels risk section "Red Line of Safety Warning". Then the critical safety warning distance $d_{safe}$ is calculated by FLAC 3D numerical simulation of the boundary scale of karst soil cave when it finally collapses. This research method can provide a safe and reliable scientific reference for future subway Line adjustment, construction, operation and disaster relief.

Keywords  Safety Warning Distance. subway tunnels. development and management. karst collapse risk area

1. Introduction

It is an effective means to use urban underground space resources to solve urban congestion and alleviate the pressure of land use. Especially in recent years, with the rapid urban development, construction of underground tunnels has gradually been attached great importance by governments at all levels. However, in karst collapse high risk area, when exploiting underground space resources, karst collapse would often occur without any obvious signs beforehand, and cause inestimable losses
afterwards, especially irreparable losses to underground tunnel projects under construction or underground traffic projects under operation (Jia 2018). In order to make rational use of underground space resources and avoid disasters scientifically, a series of challenges have been brought to departments and scientific researchers of urban underground space resource management in karst collapse risk areas. And whether the scope of karst collapse can be quantitatively predicted is of great significance to actual underground engineering construction. In other words, the construction of underground tunnels in areas beyond the scale of karst collapse or the influence of stress and strain was safe (Su 2008; Xiao 2014). Therefore, this paper puts forward the concept of "Safety Warning Distance" to study how to reasonably set Distance Waring Red Line in karst collapse risk area (Fig. 1), which is of strong scientific research value for urban underground space resource planning, subway tunnel safety construction and operation management. While how to determine the red line safety warning distance on ground still remains to be studied in depth. If it is conservative, too large value of safety warning distance will lead to difficulties in emergency rescue and low efficiency. If the value of safety warning distance is too small, rescue within the red line may lead to secondary disasters.

![A. Karst collapse in Yuejiaqiao Town, Yiyang City, China (people was watching without consciousness of red line of safety warning)](image1)

![B. Karst collapse in Yuexiu District, Guangzhou City, China (people were watching due to no red line of safety warning set up)](image2)

![C. Karst collapse in Liunan District, Liuzhou City, Guangxi Province, China (lack of red line planning for residential construction in Karst risk areas)](image3)

![D. Metro collapse site in Dalian City, China (unreasonable red line of safety warning setting)](image4)

![E. Disaster rescue in a city of southern China (whether the rescue machinery was beyond the reasonable red line)](image5)

![F. Disaster rescue in the collapse area (whether the rescue machinery was beyond the reasonable red line)](image6)

Fig. 1 Typical karst collapse cases in China
2. Research Idea

Currently, research on how to determine the red line distance of ground safety warning for karst collapse is scarce according to literature. Galve et al. (2012) proposed the concept of critical stability angle $\theta$ for ground subsidence, $\theta = \frac{\pi}{4} + \phi$, $\phi$ represents the effective friction angle of the soil, but it only regards the inner wall of the soil cave as a vertical soil without brackets, so the calculation error is large. Zhang (2015) used FLAC 2D numerical calculation method to analyze the critical stable slope angle of the inner wall of the cave after collapse, and obtained the recommended safe warning distance of the cave. Liu et al. (2015) considered the spatial effect of soil cave collapse and modeled it according to the axisymmetric model, and tentatively proposed a method for critically stable slope angle and surface safety warning distance of the inner wall of the soil cave. Based on the finite element method and the orthogonal theory, Qu(2017) established three kinds of computational models for the hidden caves above, below and on sideways of the tunnel, analyzed the influence of the hidden caves around the tunnel on the tunnel, and determined the safety thickness of hidden caves around mine tunnel by mining method. These research results provide good idea for the author to further study the red line of safety warning. As known, when the karst soil cave finally collapses, the maximum caliber will not exceed the diameter of the karst cave, and it will form a cylindrical collapse pit. If the stability of its side wall does not meet the stability requirements, it will cause secondary collapse and become a funnel (Wei et al. 2018). The size of the funnel-shaped collapse determines the distance of the red line of safety warning (Fig. 2).

As can be seen from Figure 2, when the thickness of overburden $T$ is fixed, the scale of funnel-shaped collapse pit has a direct mathematical relationship with the critical slope angle $\beta$, that is, $a_{\text{safe}} = T \times \tan \beta$. Considering the space effect after the cave collapse, the critical slope angle $\beta$ can be determined by FLAC 3D numerical simulation of the boundary scale of the final cave collapse, and then the critical safety warning distance $a_{\text{safe}}$ can be calculated.

![Figure 2 Diagram of Red Line Distance of Tunnel Safety Warning in Karst Area](image)

*Figure 2 Diagram of Red Line Distance of Tunnel Safety Warning in Karst Area*

(① vertical column collapse, ② funnel-shaped collapse; $R$ is the equivalent radius of funnel-shaped collapse crater; $R_0$ is the radius of the vertical column collapse crater, the initial span the arched soil cave is $2R_0$; $T$ is the thickness of overburden layer above an open karst cave, from bedrock surface to ground surface)
3. Basic Situation of Research Area

Xuzhou in Jiangsu province is the only karst groundwater as the city's main water supply source, according to statistics, covered karst accounts for 85% of the urban area of Xuzhou, and karst collapse risk area accounts for more than half of the covered karst area. Since 1986, there have been 12 karst collapses, forming 19 collapse pits. All three metro lines planned in the future will all pass through the risk area of karst collapse (Figure 3). Historically, the karst collapse disasters mainly concentrated in the Xi'an Station and Cultural Center Station areas. The nearest collapse area is only 10 meters away from the Metro line. If metro line planning is really less scientific management, it will bring a series of difficulties to the construction of Xuzhou metro tunnel operation and karst groundwater water ecological red line control. Next, the application of this method is illustrated by taking the risk area of karst collapse near Xi'an Station as an example.

According to the related data of previous site survey and engineering geological drilling, the center of collapse area is 17m away from Metro line, the thickness of overburden layer \( \gamma \) is 12m, in which the thickness of sandy soil is 5m, the thickness of silty soil is 7 m, and the karst water level in the case of karst collapse is 11.8m. According to geophysical prospecting and interpretation, the diameter of the nearest karst soil cave to the subway tunnel is about 5 meters, and the diameter of the opening of the karst cave is about 5.5 meters. The respective physical and mechanical properties of the overburden layer are detailed in Table 1.

From the table, it can be seen that in the shearing strength indicators, the internal frictional angle \( \phi \) and cohesive force \( c \) were low, while firmness Coefficient \( f_s \) is the relative value characterizing anti-fracture capacity of rock-earth mass. According to grading of firmness coefficient of rock-earth mass, as the firmness coefficient of covered soil at this monitored site is all smaller than 1, and the soil is basically soft, i.e. soil's anti-failure capacity is weak. Meanwhile, lateral pressure coefficient of...
covered soil \( k^0 \) is smaller than 1, implying horizontal effective stress is smaller than vertical effective stress.

**Table 1** Physics mechanical indices for soil in karst collapse area

| Index       | Weight \( \gamma \) (KN/m³) | Water Content \( w(\%) \) | Void Ratio \( e \) | Saturation \( Sr(\%) \) | Cohesive Force \( c \) (KPa) | Internal Frictional Angle \( \phi^c \) | Lateral Pressure Coefficient \( k_0 \) | Firmness Coefficient \( f_k \) | Permeability Coefficient \( K(m/s) \) | Modulus of Volume Elasticity \( K(MPa) \) | Shear Modulus \( G(MPa) \) | Tensile Strength \( Rm(Pa) \) |
|-------------|---------------------|-------------------|--------------|-----------------|------------------|-----------------|----------------|----------------|----------------|----------------|----------------|-----------------|
| Sandy soil  | 20                  | 21.7              | 0.68         | 88              | 10               | 28.5            | 0.42           | 0.5            | 1.35 x 10⁻⁶    | 13.5           | 85             | 1.35 x 10⁻⁶      |
| Silty soil  | 18                  | 23.6              | 0.60         | 96              | 56               | 11.9            | 0.5            | 0.8            | 1.6 x 10⁻⁶     | 14.6           | 6.2            | 3.22 x 10⁻⁶      |
| Limestone   |                     |                   |              |                 |                  |                 |                |                |                | 8600           | 521            | 9.66 x 10⁶       |

(Dates cited from Xuzhou Area Karst Collapse Survey Projects, China Geological Survey No.12120114022001)

4. Establishment of Numerical Calculation Model and Selection of Parameters

FLAC 3D has outstanding advantages in simulating the changes of displacement, stress and plastic zone. In order to make the model more convincing and representative, the length, width and height of the model are set to be \( 20 \times 10 \times 12 \) m³, the thickness of the upper cover soil is 12 m (sandy soil is 5 m, silty soil is 7 m), and the thickness of the lower limestone is 2 m; the karst cave is a circular platform cave with an opening diameter of 5.5 m, and the initial shape of the soil cave is approximately spherical with a diameter of 5m(Figure 4).

![FLAC3D 5.00](image)

**Fig.4 Schematic Diagram of Numerical Model (Section Plane)**

In Flac3D numerical simulation, the displacement constraint boundary is mainly used to restrict the displacement values around the model and at the bottom of the model. The boundary conditions are set as follows:

The displacement constraint boundary to restrict the place where \( x = 10 \) m, and make its displacement 0.

The displacement constraint boundary to restrict the place where \( x = -10 \) m, and make its displacement 0.
The displacement constraint boundary to restrict the place where \( y = 0 \)m, and make its displacement 0. The displacement constraint boundary to restrict the place where \( y = 10 \)m, and make its displacement 0. The displacement constraint boundary to restrict the place where \( z = -2 \)m, and make its displacement 0.

In the process of modeling, the selection of geotechnical parameters is mainly based on experimental data presented in Table 1.

5. Results Analysis of Numerical Simulation

According to the water level monitoring record, near the Xi'an Station karst collapse point, the karst water level fluctuated rapidly due to tunnel drainage during the period from August 15, 2013 to August 23, 2013 (Fig. 5).

Before August 15, the tunnel construction had not pumped water rapidly, and the water level was about 6.8m deep. The overburden soil was basically in a natural equilibrium state. Only the tension damage around the karst soil cave was dominant (Fig. 6-A).

On August 18, when the water level was about 10.5 m deep, the vertical displacement and deformation around the karst soil cave increased obviously. Due to the difference of the structure of the overburden, it is obvious that the area of the plastic zone in the sandy stratum above the overburden increased and was funnel-shaped (Fig. 6-B).

![Fig. 5 Variation Curve of Water Level in Karst Collapse Area](image)

With the increase of water level decline, the depth of water level was 11.5 m on August 21. From the numerical simulation, it can be seen that soil particles near the karst soil cave were basically in unstable state. At the same time, the cloud value of displacement and deformation in the center of the overburden layer was higher and sank into the direction of the karst soil cave. At this time, the plastic
zone near the karst soil cave basically connected with the plastic zone of the overburden layer (the penetration of plastic zone means the occurrence of karst collapse) (Figure 6-C); On August 23, it was obvious that the area with large displacement and deformation was funnel-shaped, and the surface of the overburden collapsed (Fig. 6-D).

A. Natural Equilibrium State(before August 15)

B. Mid-term (August 18)

C. Mid-term (August 21)

D. Later Period (August, 23)

Fig. 6 Variation characteristics of vertical displacement and plastic zone of overburden soil
At this time, the critical slope angle $\beta$ is calculated by the funnel-shaped collapse boundary (Fig. 6-D) derived from the numerical simulation results, and it is about 35-38 degrees. When calculating the distance of red line safety warning, the critical slope angle $\beta$ is taken as 38 degrees, and according to $a_{safe} = T \times \tan \beta$, it can be calculated that $a_{safe} = 12 \times \tan 38^\circ = 9.38m < 17m$, which indicates that the subway tunnel is safe beyond the scope of safety warning, and is in line with the rescue situation on the spot at that time.
6. Conclusion

In view of the fact that there is no reasonable research achievement in calculating the red line distance of safety warning in karst collapse risk area at home and abroad, this paper uses FLAC 3D to carry out numerical simulation to determine the critical slope angle $\beta$, and then calculate the critical safety warning distance $d_{\text{safe}}$ based on the research idea. After verification in combination with the collapse cases near Xuzhou Metro, In this paper, the critical slope angle to avoid the occurrence of disasters is a meaningful research methods, and the research results can provide scientific basis for the development and management of underground tunnels and disaster relief.

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