Development characteristic and formation mechanism analysis of collapse sinkholes in Wugaishan town, Chenzhou city, Hunan province, China

Zongyuan Pan¹,², Xuejun Chen¹, Xin Yang¹, Yu Song¹, Rulong Ban¹, Mingzhi Zhang¹
(¹. College of Civil and Architecture Engineering, Guilin University of Technology/ Guangxi Key Laboratory of Geomechanics and Geotechnical Engineering, Guilin, Guangxi 541004, China; ². Institute of Karst Geology, Chinese Academy of Geological Sciences/ Key Laboratory of Karst Dynamic, Ministry of Natural Resources & Guangxi Zhuang Autonomous Region, Guilin, Guangxi 541004, China)

Abstract: The cover collapse sinkholes occurred and concentrated in Wugaishan town, Chenzhou city since 1996. The results are combined with results of site investigation, geophysical prospecting and in situ groundwater monitoring data, allowing the development characteristics and formation mechanism of surficial collapse incidents to be summarized. Collapse sinkholes are significantly active in recent years and mostly develop in the rainy season ranging from April to June and generally show a zonal distribution along the topography of study area from SW to NE. 92.31 % of total collapse events occurred in the thickness of overburden material ranged from 0 to 15 m, which indicated that overlying material less than 15 m was easier to collapse. The results show that collapse sinkholes have strong relationship with characteristic of overburden material, which sharply decrease in internal physical and mechanical property of bottom layer. Furthermore, substantial cavities formed within bedrock are the best transport channels and storage spaces for the unconsolidated material, especially under the condition of dynamic undulation of groundwater level. The formation mechanism of collapse sinkhole is divided into three types: infiltration erosion, coupling air implosion with vacuum cavitation and saturation erosion. Each formation mechanism is related to changes of groundwater level. When groundwater level rose above the soil-bedrock interface, saturated subsoil were easier to disintegrate into small particles and migrate downward as the vertical seepage of groundwater. The hydraulic gradient increased and became the predominant factor for the development of soil cavity as groundwater level dropped below the soil-bedrock interface. Moreover, when groundwater level sharply surged up at the relative sealed environment, the upward erosion roof of cavity would be more likely to collapse by the entrapped air blasting.

Key words: Cover collapse sinkhole; Development characteristic; Affecting factor; Groundwater level; Formation mechanism

0 Introduction

Cover collapse sinkhole, the most common geological hazard in karst area, are widespread in Iran, Italy, Spain, Turkey and Canada, et al., and result in severe damage to civil private property and human-made infrastructures such as buildings and roads (Gutiérrez et al., 2008; Guerrero et al., 2008; Gutiérrez et al., 2014; Ozdemir, 2015; Gutiérrez et al., 2016; Zhou et al., 2020). Cover collapse sinkhole is a karstic geological phenomenon that overlying materials are deformed and collapsed induced by subsurface dissolution and internal erosion and formed ground-surface collapse pits, which commonly hidden from direct observation before forming surface manifestation (Lucha et al., 2008; Frumkin et al., 2011; Dai et al., 2017). They may induce by either natural causes or human activities and developed progressively or suddenly (Huang, 2009). Moreover, the occurrence and result of collapse incidents may be related to one kind or a variety of mechanisms, but a certain mechanism can be confirmed as predominant factor (Kang, 1992; Waltham et al., 2005; Beck, 2005). Therefore, the development characteristic and formation mechanism is the primary problems that being concerned by most scientific researchers (Wei et al., 2015; Xie et al., 2015). Chen et al (2014) suggest that the main factors influencing karst collapse include intensity of the karstification, characteristics and thickness of the soil cover. Hua et al (2015) analyze the spatial-temporal distribution and
formation mechanism of karst collapse, mining-induced collapse and ground-surface subsidence in Xuzhou city, Jiangsu province, China. Yang et al (2017) propose that 97.5% of karst collapse was distributed in clay with layer thickness of 1-10 m and groundwater is the most important trigger in Qianzhong plateau table. Zha et al (2020) report the occurrence of collapse sinkholes mainly affected by drainage of surrounding mines in Chaoshan area of Tongling city, Anhui province, China. Up to now, the development characteristic and formation mechanism of collapse sinkholes can’t reach unanimous conclusion due to different geological environmental backgrounds in collapse events, even though a great many efforts have done to research (Gao et al., 2013).

The carbonate rocks in Chenzhou city encompassing an area of 137.2 km² are distributed in the direction of NE, which generally exceed one third of regional area. A large number of collapse sinkholes occurred as a result of engineering-related activities such as dewatering, which to meet the need of urban water supply and orebody extraction since 1950s (Chen, 1988; Peng et al., 2001; Yin et al., 2005; Li et al., 2007). Then, a series of policies about exploitation limits of groundwater published by the Chenzhou municipal government since 1980s, which had relieved collapse sinkhole hazard to a certain extent (Liu et al., 2013). But collapse sinkholes are likely to occur once again as engineering and geological conditions changing, especially exploitation amounts of groundwater exceeding maximum magnitude, and give rise to disastrous consequences (Xu et al., 2004; Li et al., 2007). For example, as reported by Luo et al. (2008) and Wu et al. (2013), a large number of karst collapses suddenly occurred when groundwater exploitation exceeding the karst water safety exploitation quantity. However, the development characteristic and formation mechanism of collapse sinkholes following mining activities has not been clearly discussed. In 2019, with financial support from Ministry of Natural Resources of the People’s Republic of China, a comprehensive method of in-situ investigation, geophysical detecting and groundwater monitoring station were launched in Chenzhou city, aiming to better understand formation mechanism of collapse sinkholes. The result may also serve as a reference to apply to other mining-induced sinkholes.

1 Regional geological and hydrogeological setting

![Fig.1 Location and geological map of the study area. A refer to Shuangyuanchong village. B refer to Fengshuxia village.](image-url)
Table 1  Summary of the stratum in study area

| ID | Stratigraphic age | Code | Thickness (m) | Lithology |
|----|------------------|------|--------------|-----------|
| 1  | Quaternary       | Qbh  | 0-57         | Clay, silty clay and strong weathered sandy conglomerate |
| 2  | Substratum of Xikuangshan formation, Upper Devonian | D3x1 | 315-351 | Medium-beded limestone and marlrite |
| 3  | Supperstratum of Shetianqiao formation, Upper Devonian | D3s2 | 128-148 | Banded argillaceous limestone, sandy marlite interbeded with medium limestone |
| 4  | Substratum of Shetianqiao formation, Upper Devonian | D3s1 | 157 | Thick limestone and banded marlrite |
| 5  | Middle stratum of Qiziqiao formation, Middle Devonian | D2q2 | 164 | Thick limestone interbeded with thin marlrite |
| 6  | Substratum of Qiziqiao formation, Middle Devonian | D2q1 | >129 | Thick dolomite and limestone with chert nodules |
| 7  | Supperstratum of Tiaomajian formation, Middle Devonian | D2t2 | >208 | Thick fine particle quartz sandstone, siltstone and silty shale |

The study area, which is characterized with geomorphology of middle and low mountain and karst valley, located at the southeast of Chenzhou city. It is in the surrounding of Wangxian mountain and Qianli mountain with elevation varied from 390 to 1130.4 m above mean sea level. The regional stratum formations consist of upper Devonian and middle Devonian. The stratum formations of upper Devonian could divide into three types: substratum of Xikuangshan formation (D3x1), upperstratum of Shetianqiao formation (D3s2), and substratum of Shetianqiao formation (D3s1). Moreover, stratum formations of middle Devonian were composed of middle stratum of Qiziqiao formation (D2q2), substratum of Qiziqiao formation (D2q1) and supperstratum of Tiaomajian formation (D2t2). Table 1 presents the detailed lithology of study area.

The cover area of magmatic rock through investigation is approximately 24.5 km² that accounts for 36.19% of the total regional area. The lithology of magmatic rock mainly consists of granite that constitutes as the Wangxian mountain and Qianli mountain, with peak elevation of 1130.4 m and 890 m, respectively (Fig. 1). The distribution characteristic of magmatic rock, intrusion age ranging from Indosinian to late Yanshanian, is influencing by NW and NE geological structure.

In the study area, the karst aquifer formations consist of D2q1, D2q2, D3x1 and D3s1, which are characterized with fissure conduit and cavity conduit groundwater flow and good water-abundance ability. Besides, the aquifers are composed of D2t2 and D3s2. Rainfall is the main source of groundwater recharging in study area. Groundwater flow from northeast to southwest in Fengshuxia village, whereas flow direction of groundwater is mainly from southwest to northeast along the karst valley in Shuangyuanchong village attributed to topographic difference.

Structurally, Nanling fault zone in the direction of EW pass through the study area, meeting Guiyang—Chenxian fault zone along EW and the Ruxian—Rucheng fault zone of SN-oriented. Moreover, Chaling—Yongxin tectonic depression belt and Zixing—Yizhang fault zone intersect on the southern part of study area. The Shuangyuanchong village is located in west limb of the Wugaishan anticline, whereas the Fengshuxia village lies on east limb of the Wangxianling fault and Wugaishan fault.

The study area is characterized by subtropical monsoon climate with annual average temperature of 27.8 degree. The annual precipitation in study area ranges from 1029.5 to 2209.4 mm and mostly concentrates in 5 months from March through July, which has monthly maximum precipitation of 712.3 mm.

2 Development characteristics of collapse sinkhole
2.1 Morphology characteristic of sinkholes
Table 1 Summary of cover collapse sinkholes

| ID  | Shape (m) | Diameter or Major axis/Minor axis (m) | Major axis direction (degree) | Date | Depth (m) | ID  | Shape (m) | Diameter or Major axis/Minor axis (m) | Major axis direction (degree) | Date | Depth (m) |
|-----|-----------|--------------------------------------|-------------------------------|------|-----------|-----|-----------|--------------------------------------|-------------------------------|------|-----------|
| S1  | Circle    | 2.5                                   |                               | Apr-20 | 3.2      | S27 | Circle    | 3.1                                   |                               | Jun-14 | 3.6     |
| S2  | Circle    | 2.0                                   |                               | Jun-10 | 2.5      | S28 | Circle    | 4.6                                   |                               | Jun-14 | 3.8     |
| S3  | Irregular | 5.5                                   | 140                           | May-10 | 2.5      | S29 | Circle    | 2.2                                   |                               | Apr-15 | 2.1     |
| S4  | Circle    | 2.2                                   |                               | Jun-10 | 1.5      | S30 | Circle    | 1.2                                   |                               | Apr-20 | 1.2     |
| S5  | Ellipse   | 2.1                                   | 143                           | Jun-10 | 1.2      | S31 | Circle    | 4.2                                   |                               | Apr-10 | 3.0     |
| S6  | Circle    | 6.0                                   |                               | Jun-10 | 6.0      | S32 | Ellipse   | 6.0                                   | 86                            | Apr-10 | 2.0     |
| S7  | Circle    | 2.0                                   |                               | Apr-20 | 2.2      | S33 | Circle    | 5.3                                   |                               | Apr-10 | 3.0     |
| S8  | Circle    | 2.4                                   |                               | Jun-10 | 1.6      | S34 | Circle    | 2.3                                   |                               | Jun-21 | 2.0     |
| S9  | Circle    | 2.6                                   |                               | Jun-10 | 2.0      | S35 | Circle    | 2.0                                   |                               | Apr-24 | 1.5     |
| S10 | Circle    | 10.5                                  |                               | Jun-10 | 4.5      | S36 | Circle    | 2.2                                   |                               | Apr-16 | 2.5     |
| S11 | Circle    | 1.3                                   |                               | Jun-1 | 0.5      | S37 | Circle    | 4.2                                   |                               | May-15 | 2.8     |
| S12 | Circle    | 1.8                                   |                               | Jun-1 | 1.5      | S38 | Circle    | 2.2                                   |                               | May-10 | 1.2     |
| S13 | Circle    | 6.0                                   |                               | Jun-10 | 2.5      | S39 | Circle    | 4.8                                   |                               | Sep-17 | 1.5     |
| S14 | Circle    | 6.0                                   |                               | Jun-12 | 4.0      | S40 | Ellipse   | 4.6                                   | 168                           | Sep-5  | 1.4     |
| S15 | Circle    | 2.0                                   |                               | Jun-12 | 1.5      | S41 | Circle    | 1.6                                   |                               | Oct-25 | 1.4     |
| S16 | Circle    | 2.3                                   |                               | Jun-16 | 1.6      | S42 | Ellipse   | 8.3                                   | 52                            | May-10 | 3.0     |
| S17 | Circle    | 2.8                                   |                               | Jun-16 | 0.7      | S43 | Circle    | 2.8                                   |                               | Apr-17 | 2.5     |
| S18 | Circle    | 4.2                                   |                               | Sep-18 | 2.0      | S44 | Circle    | 4.2                                   |                               | Apr-17 | 3.0     |
| S19 | Circle    | 3.5                                   |                               | May-10 | 3.2      | S45 | Circle    | 1.8                                   |                               | Jul-1  | 1.5     |
| S20 | Circle    | 2.0                                   |                               | Apr-30 | 4.5      | S46 | Circle    | 1.9                                   |                               | Apr-10 | 1.5     |
| S21 | Circle    | 9.0                                   |                               | Apr-18 | 4.8      | S47 | Ellipse   | 4.1                                   |                               | Apr-12 | 1.2     |
| S22 | Ellipse   | 1.5                                   | 42                            | May-20 | 13       | S48 | Circle    | 3.4                                   |                               | Apr-21 | 1.5     |
| S23 | Circle    | 16.0                                  |                               | Jun-10 | 10.0     | S49 | Circle    | 1.6                                   |                               | Apr-20 | 1.5     |
| S24 | Circle    | 0.5                                   |                               | Apr-10 | 1.3      | S50 | Circle    | 3.0                                   |                               | Jun-13 | 1.2     |
| S25 | Ellipse   | 20.0                                  | 158                           | Jun-11 | 6.0      | S51 | Ellipse   | 1.5                                   | 76                            | Jun-12 | 1.0     |
| S26 | Ellipse   | 6.0                                   | 5                             | Jun-11 | 2.0      | S52 | Ellipse   | 3.3                                   |                               | Jun-15 | 1.6     |

Cover collapse sinkholes have posted a significantly devastating threat to villagers in study area. Table 2 listed 52 cover collapse sinkholes have occurred between 1996 and 2020. The sinkholes vary over a wide range of sizes and shapes, which are generally circular and elliptical in plan but vary in cross-section from cylinder shaped through saucer shaped to cone shaped. As shown in Table 1, sinkholes in circular, elliptical and irregular shape accounted for 83.05%, 15.25% and 1.69% of total sinkhole amounts, respectively. Figure 2 shows the typical collapse sinkholes in study area. Furthermore, sinkholes in cylindrical shape accounted for 76.79% of total sinkhole amounts, besides others only held 23.22% of total sum.

Fig.2 Cover collapse sinkholes of different sizes in study area. a Collapse sinkhole 3 m in diameter at a dried up pond, right of the photo is north. b Irregular sinkhole in Fengshuxia village (long axis and short axis is 3 m and 1.5m, respectively), top of the photo is north.
Depending on the type of sinkholes under discussion, collapse sinkholes were ranging from 0.5 in diameter and 0.5 m in depth for small collapse sinkhole, to 10 m or more in diameter and 10 m deep for larger sinkholes. The biggest sinkhole is S25, which has elliptical shape on the surface with a long axis of 20 m and short axis of 12 m, and a depth of 6 m. However, most sinkholes were small size in study area. Figure 3(a) shows 39 collapse sinkholes with diameter of smaller than 5 m accounted for 75% of total sinkholes, whereas sinkholes with diameter of 5~10 m, 10~15 m and 15~20 m made for total sinkholes of 17.31 %, 1.92 % and 5.77 %, respectively. On the other side, the depths of sinkholes were mostly smaller than 3 m, but eleven sinkholes were larger than 3 m in depth that accounted for 21.15% of total sinkholes.

![Fig3](image)

**Fig.3** Morphology characteristic of cover collapse sinkhole in study area. a Plane size distribution of cover collapse sinkhole. b Depth distribution of cover collapse sinkhole.

### 2.2 Temporal and spatial distribution of sinkholes

#### 2.2.1 Temporal occurrence of sinkholes

As shown in Fig. 4(a), 90.38 % of collapse events occurred in the rainy season ranging from April to June. Nevertheless, twenty-three (44.23 %) collapse sinkholes occurred in June, while eighteen (34.61 %) and six (11.54 %) collapse events took place respectively in April and May. Meanwhile, Figure 3(a) shows that only 9.62 % of collapse sinkholes occurred between July and October. The monthly distribution of collapse sinkholes suggests that intensity of sinkholes is generally related to precipitation.

Figure 4(b) shows that earliest collapse incidents took place in the 1990s, but sporadic sinkholes occurred in the next few years. There were six collapse events in total occurred during 1996 and 2009, which was made for 9.61 % of total sinkholes amounts. However, a large amount of collapse sinkholes occurred in 3 years from 2012 through 2014, with maximum amounts of sixteen sinkholes occurred in 2013, then annual sinkhole amounts gradually declined. Furthermore, the occurrence rate of sinkholes increased again since 2017, reached the maximum amounts of sinkhole in 2019. In general speaking, collapse sinkholes mostly occurred during 2012 and 2020, which seemed like in connecting with mining activity.

![Fig4](image)

**Fig.4** Temporal occurrence of cover collapse sinkhole. a Monthly occurrence of cover collapse sinkhole. b Annual occurrence of cover collapse sinkhole.
2.2.2 Spatial distribution of sinkholes

Collapse sinkholes mainly distributed in the two villages, with twenty-seven sinkholes concentrated in Fengshuxia villages and twenty-five in Shuangyuanchong village. Both villages were located in karst valley that collapse incidents mainly distributed NE along the karst valley. The stratum lithology underlain the two villages were substratum of Qiziqiao formation of the Devonian, which consisted of gray thick limestone. On the other hand, the overburden materials overlying the bedrock could be divided into single layer and bilayer structure, among which single layer structure is composed of clay or silty clay while bilayer structure is consisted of clay or silty clay and clayey pebble. Table 2 shows 32 collapse incidents occurred in soil strata structure of single layer, which accounted for 61.54% of total sinkholes, whereas 20 sinkholes took place in sediments structure of bilayer. In addition, detailed analysis of soil strata thickness on collapse events are provided below: collapse sinkholes are generally concentrated on thickness of overburden material less than 10 m, which accounted for 92.31 % of total amounts. Meanwhile, approximately 44.23 % of sinkholes occurred in the overburden thickness of 0−5 m, while 48.08 % of sinkholes occurred in sediments thickness between 5 and 10 m. However, only four sinkholes took place in the overburden thickness ranged from 10 to 15 m. It indicates that collapse sinkholes are more likely occurred in the area that overburden thickness is less than 10 m. Moreover, collapse events occurred in clay had 7.7 % more than silty clay in sinkhole occurrence rate. Throughout deposit origin can be divided into el-diq and alluvial-proluvial type in study area, but it seems like collapse events occurred in el-diq soil type were more than alluvial-proluvial overburden did.

| Table 2 The relationship between characteristic of soil layer and collapse sinkhole |
|-----------------------------------------------|-----------------|-----------------|
| Characteristic of soil layer                  | Type            | Number of sinkholes | Ratio/% |
| Origin of soil layer                          | El-diq          | 35               | 67.31   |
|                                               | Alluvial-proluvial | 17              | 32.69   |
| Genre of soil layer                           | Clay            | 28               | 53.85   |
|                                               | Silty clay       | 24               | 46.15   |
| Structure of soil layer                       | Single layer structure | 32          | 61.54   |
|                                               | Bilayer structure | 20              | 38.46   |
| Thickness of soil layer                       | 0−5m            | 23               | 44.23   |
|                                               | 5−10m           | 25               | 48.08   |
|                                               | 10−15m          | 4                | 7.69    |

3 Factors affecting cover collapse sinkhole formation

The study area is in karst valley, which elevation of ground surface varied from 381 to 422 m amsl. The topography with gentle undulation reflects the intense karstification in geological past. However, because of the anisotropy in overburden material and underlying lithology, the affecting factors may be different for each sinkhole (Lei et al.2016). By means of geological and hydrogeological analysis, there are three common influencing factors contribute to the collapse incidents and the three influencing factors are presence as vulnerable characteristic of overburden materials, highly developing karstification of bedrock and dynamic fluctuation of groundwater level. The detailed analyses of affecting factors were discussed as following.

3.1 Characteristic of overburden material

The two soil types of study area are clay and silty clay. The clay is consisted of light yellow gravelly soil with thickness varied from 3 to 10.5 m. In addition, silty clay is mainly composed of grayish yellow gravelly soil, with few lead-zinc ore and pyrite and thickness between 2.2 and 11.5 m. The soil samples of study area were collected and analyzed for geotechnical parameter.

As shown in Table 3, the liquid limit and plastic limit values suggested that mechanical capacity of deposit with moisture content. The moisture content of bottom clay and silty clay increased by 10.7 % and 5.6 % respectively compared with top layer of Quaternary deposits, whereas sharply decreasing on internal friction angle and cohesion from up to down indicated that they would be susceptible to subsurface erosion when they submerged into groundwater (Lei et al., 2016). Both density and porosity of clay and silty clay presented as negative correlation. The porosity values on the bottom of both Quaternary deposit types rose by 36.84 % and 70.96 % respectively from the top layer, but density values went down to lower level from top to bottom, which
indicated overburden materials became loosened with depth. Furthermore, the values of clay and silty clay type in both internal friction angle and cohesion sharply decreased from top soil layer to the bottom.

| Type      | Depth (m) | Moisture content (%) | Density (g/m³) | Porosity | Liquid limit (%) | Plastic limit (%) | Internal friction angle (degree) | Cohesion (kPa) | Permeability (cm/s) |
|-----------|-----------|----------------------|----------------|----------|------------------|-------------------|----------------------------------|----------------|---------------------|
| Clay      | 1.25-1.45 | 25.5                 | 1.92           | 0.798    | 42.3             | 24.0              | 16.8                            | 50.5           | 3.57×10⁻⁶           |
|           | 3.65-3.85 | 25.7                 | 1.93           | 0.785    | 39.6             | 22.4              | 11.1                            | 35.7           | 4.8×10⁻⁶            |
|           | 6.1-6.3   | 36.2                 | 1.79           | 1.092    | 44.8             | 25.0              | 6.8                             | 17.9           | 8.26×10⁻⁵           |
| Silty clay| 1.6-1.8   | 21.8                 | 1.95           | 0.699    | 31.7             | 19.1              | 14.3                            | 39.6           | 2.46×10⁻⁵           |
|           | 3.2-3.4   | 21.9                 | 2.02           | 0.641    | 34.2             | 20.5              | 17.7                            | 48.5           | 3.95×10⁻⁶           |
|           | 6.4-6.6   | 26.2                 | 1.87           | 0.836    | 35.4             | 21.5              | 13.8                            | 26.7           | 4.85×10⁻⁵           |
|           | 8.4-8.6   | 27.4                 | 1.56           | 1.195    | 38.1             | 22.3              | 11.2                            | 28.4           | 4.85×10⁻⁵           |

3.2 Karstification of underlying bedrock

Fig. 5 The layout of geophysical prospecting work in study area. a Location of geophysical prospecting line in Fengshuxia village. b Location of geophysical prospecting line in Shuangyuanchong village.
It is advisable to follow a comprehensive method by combining geophysical detecting and exploratory boreholes in a phased step to ascertain karstification of bedrock. As shown in Fig. 5(a) and Fig. 5(b), seven geophysical prospecting lines were settled to detect anomalies underlain the Quaternary deposits. Ten anomalies were found in the geophysical prospecting lines through comprehensive analysis, aside from EW-oriented eight outliers (A—H) were located in Fengshuxia village, two outliers (I—J) along NE were found in Shuangyuanchong village. Taking geophysical prospecting line 2 as an example, the two anomalies were detected within the bedrock at the depth ranged from 10 to 20 m (Fig. 7). Figure 8 shows the anomalies of line 2 were interpreted as karst cavities or dissolution zone such as karstic grooves, which formed as approximately EW—oriented underlying dissolution zone on the plane view. Moreover, five anomalies within prospecting
lines were selected to verify geophysical prospecting results by drilling borehole (Fig. 6). Table 3 lists the exploratory boreholes that confronted cavities and heights of cavities and filled. Furthermore, five boreholes encountered eleven cavities within the bedrock. The karst cavities are ranged from 6.5 to 44.2 m in depth and 0.8—4.3 m in height. The largest karst cavity is explored in borehole SK01 with maximum height of 4.3 m. Approximately 90.91% of the intercepted cavities are filled with loose clay and gravel, while one cavity (9.09%) is open and water—filled. These indicated that karstification of the bedrock is highly active in the study area. The open karst cavities become favorable transfer and storage spaces for overlying cover deposits under subsoil erosion condition by direct infiltration of surface water. In addition, the unconsolidated clay and gravel filled in the karst cavities are more likely to disintegrate into smaller particles when they are submerged into groundwater then be migrated downward into conduits. It indicates that filled karst cavities can be emptied for overlying loosened materials deposit again.

### Table 4 The characteristic of karst cavity revealed by borehole in study area

| Borehole | Bohole depth (m) | Elevation of ground (m) | Elevation of cavity top (m) | Elevation of cavity bottom (m) | Cavity height (m) | Cavity fill      |
|----------|------------------|-------------------------|-----------------------------|-------------------------------|------------------|-----------------|
| SK01     | 100              | 401.24                  | 389.04                      | 388.24                        | 0.8              | Open            |
|          |                  |                         | 381.24                      | 376.94                        | 4.3              | Clay            |
| GK02     | 50               | 393.79                  | 380.79                      | 377.79                        | 3                | Clay with gravel|
| GK03     | 50               | 402.26                  | 395.46                      | 394.46                        | 1                | Clay            |
|          |                  |                         | 394.86                      | 393.86                        |                 |                 |
| GK04     | 50               | 402.73                  | 396.23                      | 393.93                        | 2.3              | Clay            |
|          |                  |                         | 391.43                      | 388.73                        | 2.3              |                 |
| GK13     | 50               | 380.59                  | 347.09                      | 345.09                        | 2                | Gravel          |
|          |                  |                         | 341.29                      | 340.19                        | 1.1              |                 |
|          |                  |                         | 338.39                      | 336.69                        | 1.7              |                 |
|          |                  |                         | 336.39                      | 335.79                        | 0.6              |                 |

### 3.3 Dynamic changes of groundwater level

![Graph showing dynamic changes of groundwater level](image-url)
In order to realize the dynamic variation of groundwater, three pressure transducers were installed in borehole with the frequency of 20 min. As shown in Fig. 9(a), annual groundwater level variation of SK1 is ranged from 397.15 to 407.84 m amsl, whereas the elevation of limestone rockhead in SK1 monitoring point is 402.4 m amsl. The average groundwater level is 402.59 m amsl in rainy season, but average groundwater level declines to 398.5 m amsl in drought season. Obviously, groundwater level of SK1 drops below bedrock surface during drought season, but groundwater level rises above bedrock surface in rainy season because of rainfall recharging. There are lag time of 6 hours in SK1 after single rainfall, with groundwater level varied from 2.01 to 2.57 m.

As a result of mine dewatering, the groundwater level of GK4 was below bedrock surface since October 20, 2019 (Fig. 9(b)). The annual groundwater level of GK4 is varied from 382.68 to 393.5 m amsl while the elevation of bedrock surface is far beyond it. The fluctuation amplitude of the groundwater level in GK4 is generally small with changes of 0.7~1.4 m even if in heavy precipitation weather. In addition, Figure 9(c) shows the groundwater level of GK13 dropped below the bedrock surface before 16 January, 2020. However, groundwater level gradually exceeded the bedrock surface with distance ranged from 5.51 to 8.71 m between bedrock surface and water level. Then groundwater level of GK13 is varied from 378.1 to 379.26 m amsl.

In general, dynamic changes of groundwater level were related to collapse sinkhole in most conditions. Groundwater levels of SK1 and GK13 rose above the bedrock surface in the rainy season, whereas groundwater level of GK4 underlain the bedrock by the distance ranging from 2.1 to 12.92 m. The changed characteristics of groundwater level may act various effects on overburden soil, creating new ways of underground water circulation and empty void, and as a consequence development velocity of underlying cavity could not reach a agreement (Parise, 2015).
4 Formation mechanism of collapse sinkhole

The mechanism by which surficial ground collapse is the coupling consequences of groundwater, soil and bedrock, but each one is a little bit different (Beck, 2005; Santo et al., 2017; Santolo et al., 2018). Formation mechanism of collapse sinkhole may be divided into several types, such as subsoil erosion, entrapped air blasting, vacuum cavitation and mechanical vibration et al, which is differentiated by combination characteristic of soil layer, change of groundwater level and karstific development in bedrock (Kang, 1992; Beck, 2005; Jiang et al, 2017; Pan et al, 2018; Xia et al, 2019; Meng et al, 2020). For example, subsoil erosion initially occurred in the channelized path that formed by concentrated groundwater runoff, especially when groundwater level frequently fluctuated between soil-bedrock interface, and then collapsed when upward eroding void grew to a significant size. However, entrapped air blasting may be the predominant factor that caused upward-stopping roof collapse of cavity when the groundwater level rapidly surging up and compressing the air of voids at a relatively sealing environment. Therefore, formation mechanism by which collapse sinkhole will alter when affecting factors changed. According to hydrogeological condition and dynamic characteristic of groundwater in study area, the formation mechanism of collapse sinkholes are provided below:

1) Infiltration erosion. As shown in Fig. 10(a), karst conduits or cavities were formed underlying the overburden materials while groundwater fluctuated around the soil-bedrock interface. The soil cavity came into being due to overburden materials were saturated and disintegrated into particles and migrated downward as the groundwater level declined (Fig. 10(b)). Then, the hydraulic gradient gradually increased between surface water and groundwater because of groundwater level descended step by step so that soil cavity propagated upward by the acceleration of surface water infiltrating (Fig. 10(c)). Finally, the soil cavity collapsed and formed as a circular or elliptical shape of sinkhole on the surface as a result of internal cohesion of soil can’t support geostatic stress of overburden deposits (Fig. 10(d)).

![Figure 10 Schematic drawing of infiltration erosion in sinkhole development.](image)

2) Coupling air implosion with vacuum cavitation. Figure 11(a) shows groundwater level lies within the karst conduits or cavities that underlying the overburden materials at first. The skin layer of overburden deposit was saturated and formed the relatively sealed environment during rainfall (Fig. 11(b)). Later, groundwater...
level drastically increased because of recharging of surface water and rainfall. The abrupt changes of groundwater level could result in compression of the air between the saturated sediments and karst conduits. The implosion of the entrapped air might destroy the soil structure and form a soil cavity. As shown in Fig. 11(c), the entrapped air produced suck erosion effect for overlying deposits as groundwater level declined based on previous sealed environment, which accelerated the development of soil cavity. Eventually, collapse sinkhole occurred when groundwater level fluctuated around the soil-bedrock interface (Fig. 11(d)).

Figure 11 Schematic drawing of groundwater-air dynamic variation in sinkhole development. a Groundwater level is within the karst conduits that underlying the overburden materials. b Groundwater level drastically increases by the infiltration of surface water result in implosion of entrapped air. c Groundwater level declines causing vacuum cavitation that accelerating soil cavity propagate upwards. d Soil cavity eventually collapses due to groundwater level goes up and down repeatedly.

(3) Saturation erosion. Fig. 12(a) shows subsoil overlying the karst conduits were saturated and soften when the groundwater level rise above the soil-bedrock interface. The unconsolidated overburden deposits were easy to collapse and form the void especially in saturated condition (Fig. 12(b)). Moreover, small void of subsoil were rapidly enlarged as the vertical seepage of groundwater (Fig. 12(c)). In conclusion, roof of soil cavity collapsed as the subsoil erosion continuously proceeding (Fig. 12(d)).
Figure 12. Schematic drawing of subsoil erosion in sinkhole development. a) Groundwater level rise above the soil-bedrock interface. b) Saturated subsoil were easier to disintegrate into small particles and migrate downward as the vertical seepage of groundwater. c) Soil cavity begins to enlarge as the subsoil erosion continuously proceeding. d) Collapse incident occur as the soil cavity expanding to the certain extent.

5 Conclusion

A thorough investigation and analysis has been made of the development characteristics of collapse sinkholes and associated formation mechanism as a result of underground ore-body mining and dewatering activity in the Wugaishan area of Chenzhou city, Hunan province. The following conclusions can be drawn from the results:

(1) Fifty-two cover collapse sinkholes have occurred in the two villages between 1996 and 2020. 83.05 % of collapse sinkholes are in circular shape, whereas sinkholes in elliptical and irregular shape accounted for 15.25 % and 1.69 % of total sinkhole amounts, respectively. Approximately 75 % of total sinkholes are in small sizes with diameter of less than 5 m, but 5.77 % of the collapse events are in large scales of 15~20 m.

(2) 90.38 % of collapse events have occurred in the rainy season ranging from April to June, among which eighteen (34.61 %), six (11.54 %) and twenty-three (44.23 %) collapse sinkholes have occurred in April, May and June, respectively. All collapse events have took place in the Qiziqiao formation of the Devonian. Collapse sinkholes are mainly occurred in the area with thickness of overburden materials less than 10 m.

(3) The karsts are well developed within the bedrock in the investigated area, which is regarded as the basic condition of the collapse sinkholes. Moreover, the characteristics of overburden materials are sharply decreased from top to bottom so that they will gradually generate soil cavity and propagate upward till surficial collapse. Furthermore, dynamic changes of groundwater level causing by dewatering are the main trigger factor to collapse sinkholes.

(4) The formation mechanism of collapse sinkholes in the investigated area is related to changes of groundwater level. When groundwater level rose above the soil-bedrock interface, saturated subsoil were easier to disintegrate into small particles and migrate downward as the vertical seepage of groundwater. The hydraulic gradient increased and became the predominant factor for the development of soil cavity as groundwater level dropped below the soil-bedrock interface. Moreover, when groundwater level sharply surged up at the relative sealed environment, the upward erosion roof of cavity would be more likely to collapse by the entrapped air blasting.
Acknowledgments This work was supported by the Guangxi Natural Science Foundation of China (Grant No. 2018GXNSFAA294020), National Science Foundation of China (NSFC) (Grant No.41967037 & 41877300), China Geological Survey Project (Gran No. DD20190266), the National Youth Science Foundation of China (NYSFC) (Grant No.41402284)

References

Beck BF (2005) Soil piping and sinkhole failure. Encyclopedia of Caves (Second Edition). Elsevier. New York, pp 523-528

Chen HL (1988) The analysis of ground-surface deformation causing by dewatering in Chenzhou city, Hunan province. Carsologica Sinica 7(1): 19-25. http://doi.org/CNKI:SUN:ZGYR.0.1988-01-002

Chen LJ, Sun XL, Pi J et al (2014) Distribution characteristics and factors influencing karst collapse in Dachengqiao, Ningxiang, Hunan. Carsologica Sinica 33(4): 490-498. https://doi.org/10.11932/karst201414

Dai JL, Luo WQ, Wu YB, et al (2017) Mechanism analysis of sinkholes formation at Jili village, Laibin city, Guangxi, China. Carsologica Sinica 36(6): 808-818. http://doi.org/1011932/karst2017y59

Frumkin A, Ezersky M, Zoubi AA, et al (2011) The dead sea sinkhole hazard: geophysical assessment of salt dissolution and collapse. Geomorphology (134): 102-117. http://doi.org/10.1016/j.geomorph.2011.04.023

Guerrero J, Gutiérrez F, Bonachea J, et al (2008) A sinkhole susceptibility zonation based on paleokarst analysis along a stretch of the Madrid-Barcelona high-speed railway built over gypsum and salt bearing evaporates (NE Spain). Engineering Geoloy 102(1-2):62-73. http://doi.org/10.1016/j.enggeo.2008.07.010

Gutiérrez F, Guerrero J (2008) A genetic classification of sinkholes illustrated from evaporative paleokarst exposures in Spain. Environmental Geology 53: 993-1006. http://doi.org/10.1007/s00254-007-0727-5

Gao Y, Luo W, Lei MT (2013) Investigations of large scale sinkhole collapses, Laibin, Guangxi, China. In: Proceedings of the 13th multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst: NCKRI symposium 2, pp 327-331.

Gutiérrez F, Parise M, Waele JD, et al (2014) A review on natural and human-induced geohazards and impacts in karst. Earth Science Reviews 138: 61-88. http://dx.doi.org/10.1016/j.earscirev.2014.08.002

Gutiérrez F, Lizaga I (2016) Sinkholes, collapse structures and large landslides in an active salt dome submerged by a reservoir: The unique case of the Ambal ridge in the Karun River, Zagros Mountains, Iran. Geomorphology 254: 88-103. http://dx.doi.org/10.1016/j.geomorph.2015.11.020

Huang PL, Chen CX, Xiao GF, et al (2009) Study of rock movement caused by underground mining in mines with complicated geological conditions. Rock and Soil Mechanics 30 (10): 3020-3025. http://dx.doi.org/10.16285/j.rsm.2009.10.004

Hua XQ, Huang JJ, Miao SX, et al (2015) Distribution and causes of Geo-hazards in Xuzhou. Journal of Geological Hazards and Environment Preservation 26(2): 72-79. http://dx.doi.org/10.3969/j.issn.1006-4362.2015.02.013

Jiang XZ, Lei MT, Gao YL (2018) New karst sinkhole formation mechanism discovered in a mine dewatering area in Hunan, China. Mine Water Environ 37(4): 1-11. https://doi.org/10.1007/s10230-017-0486-9
Kang YR (1992) Collapse causing models in karstic collapse process. Hydrogeology and Engineering Geology 19 (4): 32-34. http://dx.doi.org/10.16030/j.cnki.issn.1000-3665.1992.04.014

Lei MT, Gao YL, Jiang XZ, et al (2016) Mechanism analysis of sinkhole formation at Maohe village, Liuzhou city, Guangxi province, China. Environmental Earth Sciences 75:542.

Li SX, Chen RH, Shen J (2007) The Chenzhou China pond coal mine picks depletion region of ground the influence factor and the preventing and controlling measure discussion. Journal of Geological Hazards and Environment Preservation 18(3): 19-23. http://dx.doi.org/10.1003/j.issn.1006-4362.2007.03.005

Luo ZH, Xia JH (2008) Safety exploitation of groundwater in Beihua area, Chenzhou city 30(6): 56-59. http://dx.doi.org/10.1003/j.issn.1004-1184.2008.06.017

Lucha P, Cardona F, Gutiérrez F, et al (2008) Natural and human-induced dissolution and subsidence processes in the salt outcrop of the Cardona Diapir (NE Spain). Environmental Geology 53: 1023-1035. http://dx.doi.org/10.1007/s00254-007-0729-3

Liu TS, Liu LM (2013) The investigation report of geohazards in Beihu area of Chenzhou city, Hunan province.

Meng Y, Li ZJ, Jia L (2020) An analysis of allowable groundwater drawdown and pumpage from a karst aquifer to prevent sinkhole collapses in the Pearl River Delta, China. Water Resources 47(4): 530-536. http://dx.doi.org/10.1134/S0097807820040089

Pan ZY, Jia L, Lei MT, et al (2018) Mechanism of sinkhole formation during groundwater-level recovery in karst mining area, Dachengqiao, Hunan province, China. Environmental Earth Sciences 77:799. https://doi.org/10.1007/s12665-018-7987-0

Parise M (2015) Karst geo-hazards: causal factors and management issues. Acta Carsologica 44(3): 401-414. http://dx.doi.org/10.3986/ac.v44i3.1891

Peng T, Ge ST, Wu W, et al (2001) The treatment of soil cavity collapsing area. Hydrogeology and Engineering Geology 3:55-58. http://dx.doi.org/10.1003/j.issn.1000-3665.2001.03.016

Santo A, Budetta P, Forte G, et al (2017) Karst collapse susceptibility assessment: a case study on the Amalfi Coast (Southern Italy). Geomorphology 285:247-259. http://dx.doi.org/10.1016/j.geomorph.2017.02.012

Santolo A.S.D, Forte G, Santo A (2018) Analysis of sinkhole triggering mechanisms in the hinterland of Naples (Southern Italy). Engineering Geology 237:42-52. http://dx.doi.org/10.1016/j.enggeo.2018.02.014

Waltham T, Bell F, Culshaw M (2005) Sinkholes and subsidence. Springer. Chichester, pp 157-177.

Wei YY, Sun SL, Huang JJ, et al (2015) Spatial-temporal distribution and causes of karst collapse in the Xuzhou area. Carsologica Sinica 34(1): 52-57. http://dx.doi.org/10.11932 /karst20150107

Ozdemir A (2015) Sinkhole susceptibility mapping using a frequency ratio method and GIS technology near Karapinar, Konya-Turkey. Procedia Earth and Planetary Science 15: 502-506. http://dx.doi.org/10.1016/j.proeps.2015.08.059

Xia KZ, Chen CX, Zheng Y, et al (2019) Engineering geology and ground collapse mechanism in the Chengchao Iron-ore Mine in China. Engineering Geology 249:129-147. https://doi.org/10.1016/j.enggeo.2018.12.028
Xu GQ, Shen HZ (2004) Analysis on the land collapse induced by pumping groundwater—Huainan Coal Mine as an example. The Chinese Journal of Geological Hazard and Control 15(4): 64-69. http://dx.doi.org/10.16031/j.cnki.issn.1003-8035.2004.04.014

Xie XT, Li SR, Liao YP, et al (2015) Analysis on distribution and formation of the karst collapse in Tongluoshan of Chongqing. South to North Water Transfers and Water Science & Technology 13(4): 751-755. http://dx.doi.org/10.13476/j.cnki. nsbdqk.2015.04.032

Yin RJ, Sheng ZY (2005) Karst ground collapses distribution and measures of prevention and control in Chenzhou city. Journal of Geological Hazards and Environment Preservation 16(2):143-147. http://dx.doi.org/10.3969/j.issn.1006-4362.2005.02.007

Yang YL, Yang RK, Meng FT, et al (2017) Brief analysis of distribution and influence factor of table-board shallow overburden type karst collapse in central Guizhou Plateau. Carsologica Sinica 36(6): 801-807. http://dx.doi.org/10.13476/j.cnki.nsbdqk.2015.04.032

Zha FS, Liu CM, Su JW, et al (2020) Formation conditions of karst collapse and evaluation of ground stability in Chaoshan area of Tongling city. Geological Review 66(1): 246-254. http://dx.doi.org/10.16509/j.georeview.2020.01.018

Zhou WF, Lei MT, James WL, et al (2020) Pre-glacial and post-glacial sinkholes in Silurian carbonate rocks in the James bay lowland, Canada. Proceedings of 16th multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst. Puerto Rico, pp 299-306.