Influences of Groundwater Movement on Karst Collapse Based on GIS

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Abstract. The karst area in Yuejiaqiao of Yiyang City was investigated in this study. 6 kinds of evaluation factors including large collapse pits, small collapse pits, faults, groundwater movements, depths of covering soil and human activities were particularly considered. Based on the spatial analysis functions of the geographic information system (GIS) platform and the analytic hierarchy process (AHP), a weighted calculation on the grids of the above evaluation factors was conducted to acquire the zoning map of karst collapse risks. The assessment results are accord with the actual situation as a whole. On this basis, a second assessment was carried out regardless of groundwater movements. Therefore, the influence of groundwater movements on the distribution of karst collapse was analyzed by comparing the two assessment conclusions. The results show that the groundwater movement increases the area of risk zones by 16.4% and greatly changes the distribution of risk zones. Moreover, the groundwater movement increases the risk of the investigated area by 0.1% - 0.3% depending on geological conditions.

1. Introduction
Karst collapse refers to the phenomenon of sudden collapse of the ground due to the damage caused by overburden or the roof of hidden karst in karst areas [1]. Karst collapse is a great threat to both human life and engineering facilities in karst areas; it causes serious soil erosions and worsens the environment. For example, the houses in Xiamao, Jinshazhou and Datan areas of Guangzhou City were widely affected by karst collapses. This had not only led to a great inconvenience of the residents’ daily life, but also caused huge economic losses [2]. In the past decades, karst collapses have received a great attention due to its serious harmfulness and complicated mechanisms. Baryakh and Fedoseev [3] explained the surface karst collapse and the formation of underground karst caves with Distinct Element Method (DEM). Taking Yanyupuligu as an example, Yang et al. [4] analyzed the mechanism of karst collapse.

China is one of the countries most suffered from karst collapses in the world. Soluble rocks are widely distributed in 22 Provinces and Autonomous Regions of China; they cover an area of $3.65 \times 10^6$ km², which accounts for more than 1/3 of the national territory of China [5]. Risk assessment and prediction work are of predominant significance. Because of its powerful ability in spatial analysis, Geographic Information System (GIS) has been rapidly developed and has become an important tool in geological hazard evaluations [6-10]. For example, Chen et al. [11] assessed the hazard of seismic landslides with the help of GIS technology and fuzzy mathematics theory. Using RS and GIS, Li et al.
[12] performed quantitative evaluations on the geological disaster risk of Laoshan District of Qingdao City and acquired the geological hazard zoning map of Laoshan District. Zhu et al. [13] applied the multi-source information fusion technology of GIS to the field of water inrush evaluation and prediction in coal mines. The above previous studies mainly focus on the risk assessment of karst collapses, especially the classification and prediction of karst collapse in karst area; however, the results cannot directly reflect the influence of groundwater movements on karst collapse. Other research methods usually emphasize the mechanism of groundwater effects, and thus offer no insight into the influence of groundwater movements and cannot obtain the risk of groundwater on karst collapses.

This paper aims to investigate the influence of groundwater movements on the karst collapses. To this end, two risk assessments, one considering groundwater movement and the other regardless of groundwater movement, were performed using the GIS technology. On this basis, the influence of groundwater movement on karst collapses (e.g., area, distribution and risk) were evaluated. The results of this study would provide new insight into the risk assessment and treatment of karst collapses.

2. Geology of the study area
Yuejiaqiao Town is located in the south of Yiyang City, Hunan Province. It is about 27 km away from Yiyang City and belongs to the system of Xingjian River. This town has rich water systems, abundant streams and dense reservoirs and ponds. The study area lies between the hilly central region of Hunan Province and the alluvial plain of Dongting Lake. This area is mainly the eroded hilly landforms with a small amount of karst hilly landform and erosion accumulation landform. The elevation is generally high in the north and south and low in the center.

The research area is located in the uplift belt of the northwest of Weishan - Hengyang and the northern margin of Ziyun Mountain, where the regional geological structure is complex. Faults develop in this area with the characteristics of crushing and strong mylonitization. Secondary joints and fractures also develop due to the influence of geological structures. The new tectonic movement is not developed and there is basically no new structural deformation. In this area, there are 7 major faults (5 of them are concealed faults): Henglongqiao - Pengjiazhou - Sanwanli fracture (F1), Tongjiatang - Feng Jialing - Longjiawan fracture (F2), Dawuwan - Dafengdian fracture (F3), Xujiawuqu - huaiqilng - Shuijapo fracture (F4), Songjiazhou - Meitanbai fracture (F5), Xiabianwan - Shangwan fracture (F6) and Fengshancun - Xiaojiachong - Laowu fracture (F7).

The recharge of groundwater in the research area mainly comes from the atmospheric precipitation, surface water supply and the lateral recharge of groundwater. The lateral recharge is relatively small compared to the first two supply sources. In the natural state, the groundwater in the study area flows from southwest to northeast; however, the groundwater flows from southwest to south in coal mining conditions. The two faults of F1 and F2 are the main runoff zones. The drainage of the coal mine drainage area in the south of the coal mine is discharged by the drainage of the nearby coal mine. The rich in soil hole, karst cave, karren, grooves and tectonic fracture leads to a good discharge condition of groundwater.

In the study area, there are 15 large collapse pits and 125 small collapse pits. The total area of these large collapse pits is 3359.46 m² and the influenced area is 8644.5 m². 716 ground collapses occurred in this area from October 1979 to February 2012, causing nearly 200 million yuan direct economic losses. At present, the karst collapse is a direct threat to the lives and property of local people, seriously affecting the production and living of local residents and hindering the development of the local economy.

3. Research methods
Analytic hierarchy process (AHP) is used to determine quantitative indexes or scale indexes. According to the significance of every factor on the results, the weight of each factor was calculated through the judgment matrixes. Finally, the evaluation target value of the highest level is calculated using the grid calculator function of ArcGIS.
3.1. Selection of evaluation factors
Karst collapse is affected by karst development degree, groundwater system, geological structure, geotechnical property, depth of covering soils, human activities, etc [14]. 6 evaluation factors of karst collapse in the study area are selected according to collapse perambulation report and monitoring data. These factors include large collapse pits, small collapse pits, faults, groundwater movements, depths of covering soils, and human activities.

Large collapse pits and small collapse pits. Large collapse pits and small collapse pits usually appear in the region where karst collapse has occurred. Therefore, karst is highly developed in these areas. Thus, the karst collapse is closely related to shallow dissolving groove of dissoluble rocks, the soil caves and karst caves in the contact interface between the soluble rock and the upper soil and the development of dissolving ditch [14]. The development of karst collapse is characterized by stages, synchronicity, continuity, periodicity and repeatability; it is often accompanied by surface subsidence and cracking. Several large areas of surface subsidence and cracking were found in the study area. There must be a well-developed karst cave or soil cave in the area where the collapse has occurred. Therefore, the geological conditions in this area are meet the conditions of the recurrence of karst collapses.

Faults. Tectonic movement is an important factor for the occurrence of karst collapses. Each tectonic movement will form new cave systems, resulting in karst collapses [15]. The fault structure provides necessary channels for the initial runoff of karst water in the study area. The tectonic movement provides dynamic conditions for groundwater movement and dissolution. The characteristics of faults control the zone and stratification of karst development.

Groundwater movements. The formation of karst collapse is closely related to the movement of water. Under certain conditions, groundwater has a latent erosion effect on soil. Fine soil particles are taken away by water, resulting in vadose zones, soil holes and karst collapses [16]. In the study area, there are several tributaries of the Quantico River and many streams and ponds. The groundwater mainly consists of pore water in loose rock, pore fissure water in red layered clastic rock and karst cave water in carbonate rock.

Human activities. Tirzah’s principle indicates that a higher water table has support effects on soil [17]. However, water table is, in reality, greatly changed because of the extensive extraction of groundwater for daily life and industry use. The research area is close to the coal mine, where drainage is required when mining the coal mine. This leads to the rapid decline of water table and support force and finally causes collapses. This kind of collapse is the most harmful among those caused by human activities.

3.2. Calculation of weight

3.2.1. Establishment of hierarchical structure. A hierarchical structural model of the above six evaluation factors is established, as shown in Fig. 1.
3.2.2. Construction of judgment matrix. After constructing the analytic hierarchy process (AHP) model, it is necessary to build the judgement matrix for comparison between every two factors. In order to make the relative importance of each evaluation factor more objective and quantified, the scaling method introduced by Saaty’s [18] was used. The meaning of each scale is listed in table 1.

| Scale | Meaning |
|-------|---------|
| 1     | The two factors are of equal importance |
| 3     | One factor is slightly more important than the other |
| 5     | One factor is obviously more important than the other |
| 7     | One factor is intensively more important than the other |
| 9     | One factor is exceedingly more important than the other |

Reciprocal: If the judgment value between the factor Xi and the factor Xj is $a_{ij}$, then the ratio of the importance of Xi to the importance of Xj is $a_{ij} = 1/a_{ji}$.

The scales 2, 4, 6 and 8 are the median of the above adjacent judgments.

According to Table 1, the evaluation factors were assigned and the judgment matrix was constructed, as shown in Table 2.

| Indication system (IS) | Large collapse pits | Small collapse pits | Faults | Groundwater movements | Depths of covering soil | Human activities |
|-----------------------|---------------------|---------------------|--------|------------------------|------------------------|-----------------|
| Large collapse pits   | 1                   | 5                   | 3      | 3                      | 7                      | 7               |
| Small collapse pits   | 1/5                 | 1                   | 1/5    | 1/5                    | 2                      | 2               |
| Faults                | 1/3                 | 5                   | 1      | 1                      | 6                      | 6               |
| Groundwater movements | 1/3                 | 5                   | 1      | 1                      | 6                      | 6               |
| Depths of covering soil | 1/7                 | 1/2                 | 1/6    | 1/6                    | 1                      | 1               |
| Human activities      | 1/7                 | 1/2                 | 1/6    | 1/6                    | 1                      | 1               |

3.2.3. Consistency check. The eigenvalue, the eigenvector and consistency index are calculated according to the judgment matrix.

1. The elements in each column of a judgment matrix are normalized (i.e., the sum of the elements in each column is 1):

$$b_{ij} = X_{ij}/\Sigma X_{ij}$$

(1)

Where $X_{ij}$ is the element in a judgment matrix; $b_{ij}$ is the normalized element.

2. Summation of the normalized elements in each row:

$$C_i = \Sigma b_{ij} \,(i=1,2,3\ldots n)$$

(2)

Where $c_i$ is the sum of the normalized elements in a judgment matrix.

3. $c_i$ is normalized by:
\[ Wi = \frac{ci}{\sum ci} \]  

(3)

4. Calculation of the eigenvector:

\[ W = (w1, w2, \ldots, wn) T \]  

(4)

Where \( W \) is the approximate value of the eigenvector of the matrix; \( T \) is the reciprocal of the number of elements in the judgment matrix.

5. Calculation of the maximum characteristic root (\( \lambda_{\text{max}} \)) of the judgment matrix:

\[ \lambda_{\text{max}} = \frac{1}{m} \sum_{i=1}^{m} \frac{(TR)_i}{W_i} \]  

(5)

Where \((TR)_i\) is the \( i \)th element of the vector \( TR \); \( m \) is the order of the judgment matrix.

In order to verify the consistency of the calculation results, the following equation is applied:

\[ CR = \frac{CI}{RI} \]  

(6)

Where \( CR \) is the random consistency ratio of the judgment matrix; \( CI \) is the consistency index of the judgment matrix; \( RI \) is the average random consistency index of the judgment matrix.

The value of \( RI \) is based on the \( RI \) value table of the 1-9 order matrix proposed by Saaty [18], see Table 3.

| Order | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|-------|----|----|----|----|----|----|----|----|----|
| RI    | 0  | 0  | 0  | 0.89 | 1.12 | 1.26 | 1.36 | 1.41 | 1.46 |

When the order of a judgment matrix is greater than 2, it is necessary to perform consistency checks on total sorts. If the random consistency ratio (i.e., CI) of a judgment matrix is less than 0.1, it means that the judgment matrix has a good consistency. Otherwise, the judgment matrix must be adjusted. The calculated CI of the final judgment matrix is 0.0325, which is less than 0.1. Therefore, the value of the judgment matrix is reasonable.

3.2.4. Weighting results. The final results of weight calculation are shown in Table 4.

| Evaluation factor | Larger collapse pit | Small collapse pit | Fault | Groundwater movement | Depth of covering soils | Human activities |
|-------------------|---------------------|--------------------|-------|----------------------|------------------------|-----------------|
| Weight            | 0.4082              | 0.0638             | 0.2239 | 0.2239               | 0.0401                 | 0.0401          |

It shows that the weight of large collapse pits is the largest among 6 evaluation factors, which means that large collapse pits are the key factor of karst collapse. Besides, the faults and groundwater movements also have relatively high weights. Small collapse pits, depths of covering soil and human...
activities have small weights, suggesting that these factors have little impact on the evaluation results. Notice that certain subjective factors involve in the analysis process because the evaluation index and the weight need to be determined artificially.

3.3. Treatment of evaluation factors

According to the groundwater monitoring data in Yuejiaqiao area, the assignment was made to each water level monitoring hole. The inverse distance weight method was used to calculate and normalize it. Based on the risks resulted from the depths of covering soil, the research area was divided into 4 regions varying from no impact to high impact using ArcGIS platform. The other four evaluation factors were evaluated by using the multi-ring buffer function, and hence the classification and zoning map of evaluation factors of karst collapses in Yuejiaqiao area were obtained, as presented in Fig. 2.

Fig. 2a and b shows that the collapse pits are concentrated in the northeast region of the study area and their distributions are relatively extensive, indicating that karsts are highly developed in this area. As shown in Fig. 2c, the faults cover the northeast of the study area and only a small area is not affected. Fig. 2d shows that the groundwater movements are strong in the northeast and the south. The groundwater movement in the northeast is due to natural factors, while it is mainly owing to human activities such mining in the south. As shown in Fig. 2f, the northeast of the study area, where the karsts are shallowly embedded, shows high risks. Fig. 2g shows human activities are active throughout the study area, exerting a wide influence on karst collapses. Unfortunately, the above grid layers are not processed in a comprehensive way and the predicted results may differ from the actual analysis results due to the lack of full raw data. However, it can be preliminarily predicted that high-risk areas are mainly distributed in the northeast region of the research area.
4. Calculation results
According to the weight of each evaluation factor in Table 4, weighted calculation was performed on the grid layer of all evaluation factors shown in Fig. 2 using the grid calculator function of GIS platform. Therefore, risk assessment map of karst collapses in Yuejiaqiao area was obtained. The assessment map consisted of 3 zones, i.e., high-risk zone (17.8%), moderate-risk zone (39.2%) and low-risk zone (17.8%) (Table 5 and Fig. 3).

| Evaluation result | Area / km² | Percent area / % |
|-------------------|------------|-----------------|
| Low-risk zone     | 121.66     | 43.0            |
| Moderate-risk zone| 110.83     | 39.2            |
| High-risk zone    | 50.44      | 17.8            |
| Total             | 282.93     | 100             |

Fig. 3 shows that most parts of the study area, especially the eastern region such as Luotouchong, are in the low-risk zone. The probability of karst collapse is low in this area. High-risk zones, including Yuejiaqiao, Huawuwan, Quanbiantang and Pengjiawan, are located in the northeast of the research area. Meanwhile, most of the moderate-risk zones also distributed in this area. Thus, the protection here should be strengthened. In view of the disaster distribution, one can note that large-scale collapse pits are mainly distributed in the northeast of the research area, where is also the high-risk zone. Moreover, most of the small collapse pits are also distributed in the northeast and some are located in the medium-risk zone. In the moderate-risk zone, the calculation results of the coal mine dam are high. The actual situation also indicates that the small collapse pits in the area are widely distributed. Nevertheless, the calculation results of other areas such as Pengjiawan are small. In fact, only a few small collapse pits were found in these areas. However, in the safe areas (e.g., Luotouchong), there is no appearance of disaster points. Therefore, the risk assessment results are in
accord with the actual situation, and the selection of evaluation factors and the distribution of each weight are reasonable.

Because the first calculation has ensured the accuracy of weight and evaluation factor, the second calculation can be carried out on this basis. A single calculation is not able to well consider the effect of groundwater on the karst collapses. Therefore, a second risk assessment was conducted without considering the groundwater movements. In this case, the influence of groundwater movements on karst collapses can be identified by comparing the second calculation results with the first ones.

In the second calculation, the weights of evaluation factors (except for groundwater movements) were amplified according to the original proportion so that the sum of the weights remained 1. On this basis, the weighted calculation was conducted and the results of risk assessment map of karst collapse without considering groundwater movements were obtained, as shown in Table 6 and Fig. 4.

| Evaluation result | Area / km² | Percent area / % |
|-------------------|------------|-----------------|
| Low-risk zone     | 168.33     | 59.4            |
| Moderate-risk zone| 88.13      | 31.2            |
| High-risk zone    | 26.47      | 9.4             |
| Total             | 282.93     | 100             |

Table 6. Results of karst collapse risk assessment without considering groundwater movements

Compared with the results of the first calculation (Fig. 3 and Table 5), the second calculation results show a decrease in the high-risk zone by 8.4%. The moderate-risk zone also decreased by 8.0% and varied from a wide distribution throughout the study area to a concentrated distribution in the northeast. From Figs. 2-3, one can note that the risk zones developed mainly in fault areas and karst areas. The increase in risk zones in Quanbiantang and Pengjiawan, which is in the center of the fault area, is especially considerable.
Five zones with severe groundwater movements were selected from Fig. 2 and were referred to as A - F. The maximum values of two evaluation results regarding these five zones were summarized in Table 7.

| Zone | First result | Second result | Ratio |
|------|--------------|---------------|-------|
| A    | 1.000        | 0.8397        | 1.20  |
| B    | 1.000        | 0.8169        | 1.22  |
| C    | 0.8317       | 0.6922        | 1.20  |
| D    | 0.5713       | 0.4315        | 1.32  |
| F    | 0.2514       | 0.2785        | 1.11  |

Under the influence of groundwater movements, the risks of three zones (i.e., A, B and C), which are located in karst areas, increased by about 21%. The D zone is located in the fault area and its risk increased by 32% due to groundwater movements. The F zone is situated in the safe area and is not affected by the development of karsts, faults, and groundwater movements. The risk in this zone only increased by 11%.

5. Conclusion

Based on the above investigations and analyses, the following conclusions were drawn:

1. Groundwater movements have a great influence on karst collapses. Because of the effect of groundwater movements, the risk zones (e.g., fault zone and karst zone) became widely distributed in the research area. The area of the risk zone increased by 16.4% or so. Groundwater movements showed different levels of influence on risk under different geological conditions. Due to groundwater movements, the risk increased 21% in the karst area; the risk increased 32% in the fault zones; the risk increased 11% in normal conditions.

2. The zoning map of karst collapse assessment in Yuejiaqiao area was obtained based on the spatial analysis function of the ArcGIS platform. The zoning map showed that 43.0% of the study area are in the low-risk zone; 39.2% of the study area are in the moderate-risk zone; and 17.8% of the study are in the high-risk zone located in the northeast. Therefore, the prevention and treatment of geological hazards can be carried out according to the zoning map of karst collapse risk assessment and special attention should be paid on the high-risk zones.

3. The accuracy of GIS analysis is directly dependent on the selection of evaluation factors. The rationality of evaluation factors and their weights are examined by comparing the analysis results with the practical hazard situation. On this basis, unreasonable evaluation factors are removed. The influence of evaluation factors on karst collapses can be identified by comparison analyses.

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