TYPICAL METHODS FOR FORECASTING KARST COLLAPSE IN CHINA

Yan Meng, Jianling Dai, Long Jia, Mingtang Lei

Institute of Karst Geology, Guilin, 541004, P.R. China, sinkhole@163.com, daijianling@karst.ac.cn

Feng Ji

State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu, 610000, P.R. China, 54589998@qq.com

Abstract

The aim of this paper is to describe improvements in the accuracy of forecasting karst collapse by summarizing the methods and analyzing their advantages and disadvantages. The forecasting methods were classified as geophysical surveys, monitoring of triggering factors, and strain measurements using optical fibers. Geophysical surveys can directly identify soil cavities, but the precision and depth of exploration are limited by equipment parameters and geological conditions. For example, ground penetrating radar can discover a soil cavity when the overburden layer is less than 15 m thick, and frequent scanning can determine changes in the soil cavity and predict sinkhole collapse when combined with a balance arch model. Monitoring of triggering factors is widely used to forecast karst collapse when the opening is caused by pumping, as the dynamic groundwater conditions can be acquired in real-time. However, the prediction criteria can be very difficult to obtain. In this paper we recommend a method based on the relationship between the times when anomalous monitoring data appear and the time a sinkhole opens. Using optical fibers to forecast karst collapse is the most advanced technology currently available in China. The location and time of sinkhole opening can be forecast by this method in theory, but some key issues have yet to be resolved. These issues include the strain correlation between the optical fiber and the soil, the effect of temperature on the optical fiber strain and the method of laying optical fibers in the soil. Finally, some proposals are suggested in the hope that they will generate public discussion, reducing the damage caused by karst collapse.

Introduction

In most studies of sinkholes, forecasting has been mainly based on geophysical surveys, monitoring of triggering factors, and strain measurements of the soil using optical fibers.

Geophysical survey methods have been widely applied since the 1960s to solve karst geology questions including karst collapse. Direct current (DC) resistivity techniques have been used in cave detection because of its low costs, simple field procedures and the rapid interpretation of data (Vincenz, 1968; Smith, 1986; Panno et al, 1994; Batayneh and Al-Zoubi, 2000). In recent years, ground penetrating radar (GPR) techniques have become the most popular geophysical tool for identifying and locating subsurface karst features, such as cavities, conduits and fractures (Ulriksen, 1982; Garsmueck, 1996; Martin-Crespo and Gomez-Ortiz, 2007). Other methods, such as microgravity (Arzi, 1975; Blizkovsky, 1979; Butler, 1984) and the electric-magnetic method (Kaspar and Pecan, 1975) have been used only infrequently. Geophysical prospecting methods are effective for forecasting karst collapse, but the precision, continuity and depth of the exploration are limited by equipment signal-to-noise and geological complexities.

Monitoring for trigger factors based on the groundwater pressure has become more common and can be an effective method for forecasting karst collapse (Lei et al, 2002; Li et al, 2005; Meng et al, 2006). The greatest benefit from this method is the real-time acquisition of hydrodynamic groundwater information. However, laboratory studies of the seepage deformation test have indicated that errors often appear due to discrepancies in the structures and physical-mechanical properties of the soil, even within a single layer. Thus, the smallest experimental marginal hydraulic gradient usually is adopted as a threshold for engineering safety, but this leads to a very low forecasting accuracy.

Soil strain measurement using optical fibers is the latest method for predict karst collapse. Model tests show that there is a very good relationship between the strain in the optical fiber and the soil deflection when a sinkhole opens (Jiang et al, 2006). However, some key techniques need to be implemented to understand the

strain relationship between the optical fiber and the soil (Meng and Guan, 2011).

In the paper, the principles underlying each method are introduced first, followed by some examples of the forecasting results. Finally, the merits and disadvantages of each method are analyzed and some suggestions are provided for improving the forecasting precision and reducing the harm from karst collapse.

Ground Penetrating Radar (GPR) Surveys

The simplest and most popular method for forecasting karst collapse is ground penetrating radar (GPR) in geophysical surveys. This technique can directly identify soil cavities (Figure 1). Frequent scanning using the GPR is very important to predict sinkhole openings at the ground surface. If changes in the soil cavity arch from the GPR map fit the prediction model, a sinkhole will open.

The GPR modeling for predicting the sinkhole is based on an idealized balance arch as shown in Figure 1, where: σ_v is the natural vertical stress; τ is the natural horizontal stress; h is the height of the arch; b is the half span; and f is the Protodyakonov coefficient ($f = \sigma_v/10$) (Protodyakonov, 1962). The coordinates x and y describe the location of A on the arch LOM in the Figure 2. The

equilibrium equation of the arch is $y = x^2/f*b$. Thus, if $h \leq (b^2/f*b)$, then the arch will be stable, but the hole will develop further when $h > (b^2/f*b)$ until a sinkhole opens.

Frequent scanning to monitor changes in the arch is very important, but can have high costs when the survey area is large. Moreover, GPR is not capable of mapping deep soil cavities because of equipment limitations and the complicated geological conditions.

Monitoring of Triggering Factors

Following a geological survey and risk assessment, boreholes may be constructed in high risk locations to monitor changes in the groundwater through the karst conduit (Figure 3).

Determining the forecasting threshold is a key part of the method, and laboratory testing is the most common way. First, some undisturbed soil samples are obtained, and these are subjected to geotechnical pinhole tests (Lei et al, 2002) in the lab. If the hydraulic gradient in the laboratory tests is greater than in the field, seepage deformation will generate in the soil, and a karst collapse will open at the ground surface. However, the forecasting accuracy is very low by this method due to discrepancies in the structures and physical-mechanical properties of soil even in the same layer.

Figure 1. Ground penetrating radar image of a highway in Guilin, China and the idealized model of its balance arch.

Figure 2. The idealized GPR modeling of its balance arch (Protodyakonov, 1962). σ_v is the natural vertical stress; τ is the natural horizontal stress; LOM is the arch; h is the height of the arch; b is the half span; f is the Protodyakonov (1962) coefficient; x and y are the coordinates of A on the arch LOM; R_v is the horizontal thrust at the top of arch; P is the thrust at the arch springing and T is horizontal component, N is vertical component.

Figure 3. Monitoring of groundwater pressure.

Figure 4. Relationship between timing of maximum anomalies and collapses.

To improve the forecasting accuracy, a new method based on the residual analysis of groundwater pressure was developed (Table 1). The monitoring data is anomalous when it is outside the confidence belt. The forecasting is based on relationships between the time that anomalous monitoring data were recorded and the time of karst collapse (Table 2).

The data analysis shows that the times of the maximum, minimum and most anomalous values appearing and the

time of the sinkholes opening have a linear correlation. The equation describing the relationship between the time of the maximum anomaly appearing and the time of the sinkhole opening was $y=0.965x+1356$, with a correlation coefficient was 0.998 (Figure 4). Similarly, the equation describing the relationship between the time of the minimum anomaly appearing and the time of the sinkhole opening was $y=0.98x+776.5$, with a correlation coefficient of 0.998. Finally, the equation describing the relationship between the time of the most anomalous

Table 1. Monitoring simulation data and residual errors.

ID	The monitoring time	Monitoring data(kpa)	Simulating data(kpa)	residual errors
1	8/10/2007 15:55	21.061	22.3339	-0.12729
2	8/10/2007 16:00	21.078	22.3265	-0.12485
3	8/10/2007 16:05	21.078	22.3192	-0.12412
4	8/10/2007 16:10	21.103	22.3119	-0.12089
5	8/10/2007 16:15	21.111	22.3045	-0.11935
.....				
171333	10/1/200813:40	135.45	137.7855	-0.23355
171334	10/1/200814:00	135.69	137.7866	-0.20966
171335	10/1/200814:20	135.85	137.7877	-0.19377
171336	10/1/200814:40	135.88	137.7887	-0.19087
171337	10/1/200815:00	135.97	137.7898	-0.18198

Table 2. Relationship between the timing of anomalous values and karst collapses in Guangzhou, China.

Time of sinkhole opening	Time of anomalies	Number of anomalies	Minimum anomalies (kpa)	Time of minimum anomalies	Maximum Anomalies (kpa)	Time of maximum anomalies
	10/16/2007	175				
	10/26/2007	107	-1.6027	10/26/2007 4:15		
2007-10-28 18:00	10/28/2007	34			-1.221	10/28/2007 13:35
	10/29/2007	41			-0.017	10/29/2007 11:15
	11/2/2007	361	-0.0498	11/2/2007 8:42		
	11/3/2007	23				
2007-11-7 18:00	11/4/2007	186				
2007-11-8 22:00	11/8/2007	17	-0.1925	11/8/2007 10:00	-0.2419	11/8/2007 10:50
2007-11-9 22:00	11/9/2007	26	-0.2019	11/9/2007 5:35	0.16373	11/9/2007 5:15
	11/15/2007	52	-0.3254	11/15/2007 4:05		
2007-11-18 22:00	11/17/2007	84			-0.8697	11/17/2007 9:50
	7/7/2008	11	-0.0268	7/7/2008 12:00		
2008-7-11 11:00	7/11/2008	11			-0.0287	7/11/2008 10:40
	8/19/2008	72	-0.1403	8/19/2008 8:40		
2008-9-7 12:10	8/20/2008	43			-0.0806	8/20/2008 11:20
	9/11/2008	22			-1.2286	9/11/2008 1:20
	9/29/2008	31	-1.3046	9/29/2008 19:00		
2008-10-1 15:00	9/30/2008	5				

value appearing and the time of the sinkhole opening was $y=1.043x-1707$, with a correlation coefficient of 0.998. Consequently, the time of a sinkhole opening may be predicted when an anomalous value fits the equation following monitoring. The verification of this method will be very important in the future.

Strain measurement using optical fibers

Using optical fibers to forecast karst collapse is one of the newest technologies. It has been found that there is a linear relationship between the Brillouin frequency shift (BFS, described by $V_B(\varepsilon, T)$) and the strain ε and the temperature T in the fiber optic sensor (Bao et al, 1995, Kurashima, 1993). The linear relationship can be expressed as:

$$V_B(\varepsilon, T) = V_B(0, T_0) + C_1 \varepsilon + C_2 (T - T_0) \quad (\text{Eq 1})$$

where: ε is the strain; T is temperature; $V_B(\varepsilon, T)$ is the BFS including strain and temperature; $V_B(0, T_0)$ is the BFS at the initial temperature, T_0 without strain; and C_1 and C_2

are the strain coefficient and the temperature coefficient, respectively. The feasibility of this linear relationship can be seen by the model test (Figure 5). First, optical fibers were laid in different soil layers. When the soil is damaged or changed, if the fiber can maintain the same strain changes as the soil, the strain changes in the fiber will show the changes in the soil, and thus can predict sinkhole opening at the surface.

The results show that the position of peak strain in the optical fibers corresponds to the area of disturbance and cavern formation in the soil, and the change in optical fiber strain in different soil layers indicates the vertical boundary of the area of disturbed soil (Figure 6). The time series of optical fiber strain shows the ongoing formation of areas of disturbed soil formation. In time, the Brillouin optical time-domain reflectometer (BOTDR) will become a reliable method for monitoring and predicting sinkhole collapse or subsidence, especially along linear infrastructure construction projects, such as highways and railways.

Figure 5. Model sinkhole tests using optical fibers in Guilin, China.

Discussion

Sinkholes are one of the main geological hazards in karst areas. They are very difficult to forecast due to their concealed nature and sudden appearance. Research from characterizing karst collapse formation and monitoring has identified some effective methods for predicting karst collapse, such as geophysical surveys, monitoring trigger factors, and strain measurements using optical fibers. However, some shortcomings exist for all these methods.

Geophysical surveys for real time monitoring and forecasting karst collapse can have very high costs, and the precision and depth of the exploration are limited by equipment parameters and geological conditions. Integrating geophysical surveys with other methods to identify and explore sinkholes may provide better results.

When monitoring trigger factors using groundwater, it can be difficult to determine the threshold value, and the

Figure 6. Strain curve from optical fiber during sinkhole opening

location of the sinkhole opening cannot be determined. However, some measures such as the quantity and rate of groundwater withdrawal can be controlled by this method.

Using optical fibers to forecast karst collapse is a promising new technology. The position and time of sinkhole opening can be forecast by this method in theory. However, some key factors including the strain correlation between the optical fiber and the soil; the relationship between the optical fiber strain and the soil deformation; the effect of temperature on the optical fiber strain; and laying the optical fiber in undisturbed soil are not yet resolved. We firmly believe that, although immature, this method is very promising.

These observations above are provided in the hope that they will generate more public discussion.

Acknowledgements

This work was funded by the Project of China geological survey (No. 1212011220192), the special foundation of public service of land and resources in 2012 (the Key Technologies of the Sinkhole Monitoring and Forecasting, No. 201211083), the Director Foundation of Institute of Karst Geology (NO. 2008012, 2009017), the National Natural Science Foundation (No. 40572164 and 40972231).

References

- Arzi A. 1975. Microgravimetry for engineering applications. *Geophys Prospect*, 23:408–425.
- Batayneh A, Al-Zoubi A. 2000. Detection of a solution cavity adjacent to a highway in southwest Jordan using electrical resistivity methods. *Environ Eng Geophys*, 5:25–30.
- Blizkovsky M. 1979. Processing and application in microgravity surveys. *Geophys Prospect*, 27:848–861.
- Butler K. 1984. Microgravimetric and gravity gradient techniques for detection of subsurface cavities. *Geophysics*, 49:1084–1096.
- Garsmuck M. 1996. 3-D ground-penetrating radar applied to fracture imaging in gneiss. *Geophysics*, 61:1050–1064.
- Jiang XZ, LEI MT, CHEN Y, GE J. 2006. An experiment study of monitoring sinkhole collapse by using BOTDR optical fiber sensing technique. *Hydrogeology & Engineering Geology*, 6:75–79.
- Kaspar M, Pecan J. 1975. Detection of caves in a karst formation by means of electromagnetic waves. *Geophys Prospect*, 23:611–621.
- Lei MT, Jiang XZ, Li Y. 2002. New advances in karst collapse research in China. *Environmental Geology*, 42(5):462–468.
- Li Y, Lei MT, Jiang XZ. 2006. Karst collapse monitoring in LiTang, GuangXi. *Carsologica Sinica*, 3:75–80.
- Martín-Crespo T, Gómez-Ortiz D. 2007. Collapse hazard assessment in evaporitic materials from ground penetrating radar: a case study. *Environ Geol*, 53:57–66.
- Meng Y, Yin KL, Lei MT. 2006. Probabilistic analysis on Karst collapse induced by water table fluctuation. *Carsologica Sinica*, 3:65–67.
- Meng Y, Guan ZD. 2011. A discussion on the key technical problem in monitoring and predicting sinkhole with optical fiber sensing (BOTDR) technique. *Carsologica Sinica*, 30: 187–192.
- Panno S, Wiebel C, Heigold P, Reed P. 1994. Formation of regolith-collapse sinkholes in southern Illinois: interpretation and identification of associated buried cavities. *Environ Geol*, 23:214–220.
- Protodyakonov MM (1962) Mechanical properties and drillability of rocks. In: *Proceedings of the 5th symposium on rock mechanics*, University of Minnesota.
- Smith D. 1986. Application of the pole–dipole resistivity technique to the detection of solution cavities beneath highways. *Geophysics*, 51:833–837.
- Ulriksen C. 1982. Application of impulse radar to civil engineering. PhD Thesis, University Lund, Sweden.
- Vincenz A. 1968. Resistivity investigations of limestone aquifers in Jamaica. *Geophysics*, 33:980–994.