REVIEW OF MONITORING AND EARLY WARNING TECHNOLOGIES FOR COVER-COLLAPSE SINKHOLES

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Abstract

Sinkhole collapse has become a major geohazard in many karst areas. The development of monitoring and early warning technologies is essential to investigate mechanisms of sinkhole formation. This paper reviews latest research on monitoring and early warning technologies surrounding cover-collapse sinkholes. Monitoring the hydrodynamic conditions in areas susceptible of sinkhole collapse has proven to be useful to help understand the relationship of rainfall, surface water, and groundwater in karst areas. Monitoring hydrodynamic conditions of karst groundwater includes rainfall monitoring, groundwater level monitoring, air pressure monitoring, and groundwater quality monitoring. Observations from the monitoring system and known sinkhole collapses could be used to simulate and predict hydrogeologic, geologic, and atmospheric conditions favorable to sinkhole formation. Monitoring technologies of deformation for the overburden soil include Ground Penetrating Radar (GPR), Time Domain Reflectometry (TDR), and Brillouin Optical Time Domain Reflectometer (BOTDR). GPR is more suitable

to investigate relatively flat terrain with dry soil cover. TDR and BOTDR were more suitable for linearly distributed monitoring sites because of the cohesion between soil mass and optical fiber.

Introduction

Sinkhole collapse is a dynamic phenomenon, which usually takes place in karst areas (Kang, 1984). The total karst area in China reaches 3,650,000 km², which occupies more than one-third of the territorial area of China. In the past few decades, more than 3315 sinkhole collapse events were recorded (Kang, 1984). Most of these collapse events occurred in southwestern, central, and southern China. Sinkhole collapse became a major geohazard in many karst areas in China. The sinkhole hazard not only destroyed land and infrastructure but also impacted socio-economic development and human lives and properties (Papadopoulou-Vrynioti, 2013). Due to subtle development and abrupt collapse, it is very difficult to predict and prevent sinkhole collapses. Therefore, monitoring and early warning technologies are crucial to prevent sinkhole collapse and to mitigate damage caused by sinkhole hazard.

Characteristics of Sinkhole

Sinkhole collapse is a dynamic phenomenon, which is caused by the deformation and fracture of rocks and sediments. Influential factors on the deformation and fracture could be natural or human induced (Lei, 1998).

According to the lithological characteristics of collapsed substances, sinkhole collapses could be classified into three types: cavern collapse, soil cave collapse, and non-carbonate rock roof above carbonate bedrock collapse (Williams, 1983). According to Kang (1988), 96.7% of sinkhole collapses were soil cave collapse in China (overburden material collapse) and mostly occurred in areas where the thickness of soil layer is less than 30 m. The process of soil cave collapse involved four steps: (1) groundwater took away soil particles; (2) small soil void formed and enlarged; (3) soil cave expanded near ground surface; (4) the roof of soil cave collapsed. Therefore, three conditions including flowing groundwater, soluble bedrock, and non-cohesive soil exist in most cases of cover-collapse sinkholes. However, there was no warning before most sinkholes collapses. Even though many methods have been carried out to investigate sinkholes such as field surveys, geomorphological mapping, and borehole logging (Cooper, 2008; Gutierrez and Cooper, 2002). Spatial and temporal prediction of sinkhole was immature with little success. More practical technology and tools are needed to predict sinkhole collapses and to minimize casualties and property losses.

Influential Factors on Cover-collapse Sinkhole

Sinkhole development is mainly influenced by hydrodynamic conditions, characteristics of overburden materials, and the degree of karstification of underlying bedrocks (Wu, 1999). Sinkholes are more likely triggered by multiple factors. However, single factor could be predominant in certain sinkhole collapse event.

In general, groundwater plays a significant role in the process of forming soil voids and sinkholes. Investigations of hydrodynamic conditions in recent collapse events and physical experiments reveal that sinkholes mainly occurred in the process of groundwater level decline, groundwater level rise, and groundwater fluctuations around the boundary of soil and bedrock (Jiang, 2016). Wang (2000) stated that frequent fluctuations of groundwater level not only change the state and strength of overlying soil mass but also lead to alternating normal

and negative pressures in the subjacent caves and soil voids, which eventually result in collapses.

Characteristics of overlying soil include composition, compactness, and permeability. Soil voids could form in sandy and gravelly soil because of lower cohesive force and tend to collapse after heavy rainfall (Zhu et al., 2000; Liu et al., 2000). The thicker the overburden sediment, the longer amount of time a cavity can grow, and the larger a cavity can become.

The degree of karstification of underlying bedrock is determined by the quantity and scale of cavities and fractures. Soil particles can move into cavities and fractures through the process of soil piping. If the underlying bedrock is highly karstified with large cavities and numerous fractures, the overburden soil and sediments could be easily eroded and form substantial voids and eventually trigger cover-collapse sinkholes.

Monitoring Hydrodynamic Conditions of Karst Groundwater

Monitoring hydrodynamic conditions of karst groundwater includes rainfall monitoring, groundwater level monitoring, air pressure monitoring, and groundwater quality monitoring.

Rainfall Monitoring

The recharge of rainfall and surface water would affect groundwater conditions. The fluctuation of groundwater could affect the condition and strength of overburden materials. Meanwhile, the air inside karst caves could be compressed or expanded when groundwater level fluctuated through cave conduits.

Therefore, rainfall monitoring is necessary. Rain gauge could be used to collect rain water and measure rainfall intensity. A typical rain gauge consists of event data logger and a tipping-bucket device. The rain gauge used for case studies in this paper collected rain water and recorded time, duration, rainfall amount, and temperature data. Data recording frequency was set every 10 minutes and the battery capacity could sustain at least 4 months.

Groundwater Level and Air Pressure Monitoring

The karst groundwater-monitoring network was established to monitor changes of groundwater level and temperature. Each monitoring site consisted of water pressure probe, cable, data logger, storage battery, timer,

and data transmission module (Figure 1). Data logger was used to receive and store data of water pressure through the probe and transmitted data to terminal computer via data transmission module. Storage battery supplied electric power to data logger and data transmission module and connected to a solar panel for recharge. The installation of monitoring equipment involves the following steps: (1) drill a borehole and insert a perforated PVC pipe; (2) the depth of borehole and groundwater level are estimated so a suitable water pressure probe would be selected; (3) probe should be enclosed in a gauze bag filled up with sand; (4) the borehole near the ground surface would be sealed.

Case Study 1 – Groundwater Monitoring in Dachengqiao, Ningxiang, China

A groundwater monitoring network was established to monitor changes of groundwater in May 2013 in Dachengqiao, Ningxiang, Hunan Province, China (Figure 2). The goal of this case study is to examine the development of sinkhole collapses in relation to changes of groundwater level. The ultimate goals are to better understand the formation mechanism of sinkhole collapse and to forecast sinkhole collapse events in the future. Figure 2 illustrates groundwater level changes at site yr4-1. The daily precipitation on May 18, 2013 was 30.4 mm. Groundwater level abruptly increased about 2 m and then fell back very rapidly after the rainfall even though the net change of groundwater level increased, which may indicate the overburden soil was disturbed and soil void collapse caused the anomaly of the level of groundwater. At 9:00 am on May 24, 2013, water table suddenly increased 3 m (Figure 3) and a 1 m-diameter sinkhole formed on the east side of the monitoring station (Figure 4).

Figure 1. Schematic diagram of groundwater level monitoring.

Groundwater Quality Monitoring

Groundwater quality parameters include temperature, pH, conductivity, and concentrations of cations and anions. A portable water quality meter was used to measure temperature, pH and conductivity of groundwater in the field. Additional water samples were collected using appropriate sampling bottles by following correct sampling protocols. These water samples were analyzed for cations and anions in the research lab at the Institute of Karst Geology.

Monitoring the hydrodynamic conditions would help understand the relationship of rainfall, surface water, and groundwater in karst areas. Observations from the system and known sinkhole collapses could be used to simulate and predict hydrogeologic, geologic, and atmospheric conditions favorable to sinkhole formation.

Overburden Material Deformation Monitoring

Ground Penetrating Radar (GPR)

Ground penetrating radar (GPR) has been widely used in hydrological and engineering investigations. The

Figure 2. Location of Dachengqiao, Ningxiang, China.

Figure 3. Drastic increase in water level of yr4-1 in Dachengqiao, Ningxiang, China (5/17/2013–5/28/2013).

Figure 4. A small sinkhole collapse (1m diameter) formed on the east side of monitoring site yr 4-11 in Dachengqiao, Ningxiang, China.

MALA radar system consists of control unit, shielded antenna, electrical cable, and measuring wheel. GPR system transmits electromagnetic wave through its antenna. Portions of electromagnetic waves would be reflected to ground surface when electromagnetic wave encountered abnormal medium in the process of spreading underground. The reflected waves were analyzed through terminal machine. GPR was widely used to detect and monitor deformations in rock-soil layer of geohazard area (Zhang et al, 2000; Jiang et al, 2008; Xiong et al, 2014). The detection capability of GPR is limited by hydrogeological conditions and infrastructure. For example, the travel distance of radar is affected by groundwater level, metal object, and high-voltage wire in the study area. In general, GPR is more suitable to investigate relatively flat terrain with dry soil layer.

Case Study 2 – Detecting soil voids along Guilin-Yangshuo Highway, Guangxi, China

GPR was used to locate and characterize karst hazard zones within K9–K23 section of Guilin-Yangshuo highway in Guangxi, China (Figure 5) (Lei et al., 2011). Soil voids along the highway were detected by using a GPR with the 100 MHz frequency (Figure 6). A total of 337 subsurface voids, 1–6 m in diameter, 1–5.5 m deep, and density up to 48 per 100 m, were detected using GPR.

In this work, GPR, multi-electrode electric resistivity, and shallow seismic reflection were used for a preliminary survey. Comparison of the three geophysical methods indicates that GPR can detect subsurface voids in a more effective and timely manner.

Time Domain Reflectometry (TDR)

Time Domain Reflectometry (TDR) was first used for detecting the malfunctioned segment of telecommunication cable and electric transmission line in electric power industry. It was then used to measure water content of soil in the 1980s (Topp, 1985). O'Connor et al. (2001) installed TDR under a highway for real-time monitoring of ground deformation and changes. Chen et al. (2004) investigated TDR properties of coaxial cables under different test conditions and proposed valuable conclusions for practical applications. Jiang et al. (2011) conducted a series of geotechnical and material tests in both laboratory and field settings and proved that coaxial cable could be used to monitor and forecast karst collapse under suitable conditions. The coaxial cable grouted with cement mortar was paved under places where soil voids tend to occur. The coaxial cable with cement would be fractured by the impact of overlying soil at which the soil void underneath the coaxial cable developed to a certain scale (Figure 7). Location of soil void could be determined through the TDR curve image.

Figure 5. Location of Guilin-Yangshuo Highway, Guangxi, China.

Figure 6. Detecting soil voids along Guilin-Yangshuo Highway, Guangxi, China. Left, hyperbolic anomaly in GPR profile; Right, soil voids after excavation.

5.3 Brillouin Optical Time Domain Reflectometer (BOTDR)

Brillouin Optical Time Domain Reflectometer (BOTDR) is inbuilt the optical fiber in the rock-soil mass, where soil void or sinkhole collapse tend to occur. The deformation or fracture of rock-soil mass could be detected when the status of rock-soil mass changed. The location and development rate of soil void could be calculated to forecast potential karst collapse.

Tkach et al. (1986) came up with BOTDR technology. Horiguchi et al. (1995) measured strain- and temperature-induced changes in Brillouin frequency shift. Bao et al. (2001) conducted a series of experiments both in the laboratory and outdoors and took temperature compensation into account for strain measurement. Their accuracy of strain measurement was improved to 5 m. Jiang et al. (2006) applied BOTDR to measure soil deformation in the process of sinkhole collapse in a large-scale model experiment. The experimental results showed that BOTDR would be a reliable technology to monitor and predict sinkhole collapse or subsidence, especially along linear infrastructure constructions. Guan et al. (2012) found that key factors affecting the application of BOTDR included changes of stress field distribution, void size change during the formation of the void, and the difference of responding sensitivity to the stress field change among different optical fibers.

Case Study 3 – Application of BOTDR to forecast soil void development in Chaoshan village, Tongling, Anhui, China

BOTDR was used to forecast potential soil void development in the drainage area of Chaoshan village, Tongling, Anhui, China (Figure 8). A total of 500 m optical fiber was buried along a 1 m deep and 0.8 m wide trench. Optical fiber was fixed into the bottom of

Figure 7. Schematic diagram of TDR monitoring technology for soil cave detection (Qin et al, 2010).

the trench and then backfilled with soil. Observations in 2016–2017 from BOTDR showed no obvious soil deformation in the drainage area, which indicates normal soil deposition and compaction in the study area (Figure 9). No soil voids and sinkhole collapses occurred from field investigation during the same time in the study area. Results of BOTDR monitoring agree with field investigations.

At present, TDR and BOTDR were more suitable for linear investigation because of the cohesion between soil mass and optical fiber. On the other hand, the practical application of TDR or BOTDR was mainly focused on areas close to the optical fiber.

Conclusions

Due to subtle development and abrupt onset of cover-collapse, it is very difficult to predict and prevent sinkhole collapses. Monitoring hydrodynamic conditions of karst groundwater has proven to be useful in cases of soil void development caused by rapid fluctuations of karst water table. GPR was very effective to detect soil voids in

Figure 8. Location of Chaoshan village, Tongling, Anhui, China.

Figure 9. The strain capacity of BOTDR in Chaoshan village, Tongling, Anhui, China (10/18/2016–8/11/2017) indicates normal soil deposition and compaction.

karst areas of relatively flat terrain with dry soil covers. TDR and BOTDR had some successes to monitor soil deformation along linear monitoring network. However, sinkholes are more likely triggered by multiple factors, joint application of more than 2 monitoring technologies would be necessary in many cases (Zeybek et al., 2015). Monitoring and early warning technologies are crucial to prevent sinkhole collapse and to mitigate damage caused by sinkhole hazards.

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