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Sinkholes in karst mining areas in China and some methods of prevention

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Abstract

Mining of coal, lead and zinc, gold, and iron ore deposits in karst areas has been closely associated with sinkholes in China. Surface collapse causes an increase in mine water drainage and the possibility of major water inflow from karst aquifers, which threatens the environment in mining areas and endangers the mine safety. A combination of factors including soil weight, buoyancy, suffusion process and vacuum suction can contribute to the sinkhole formation. The key measures to prevent sinkholes in mining areas are to control the amount of mine drainage, reduce water level fluctuation, seal-off karst conduits and subsurface cavities in the overlying soil, prevent water inflow, and/or to increase gas pressure in the karst conduits.

Keywords: Sinkholes; Mining; Karst; China

1. Introduction

There are three potential surface subsidence effects of underground mining, chimney collapse, trough collapse and sinkholes. Chimney collapse involves the collapse of the immediately overlying rock into the mined opening whereas trough subsidence involves the downward deflection of the overlying and adjacent rock toward the mined opening. As both collapses are hazardous to surface structures, they have been studied extensively and can be very well controlled by adjusting the mining methods (Straskraba and Abel, 1994). Unlike the first two collapses, the third surface collapse-sinkhole, refers to the surface collapse within the overburden soil rather than the collapse of roof rock. It may not take place in all mines but depends on the local geological and hydrogeological conditions. Very often, sinkholes are found in shallowly-buried karst areas and closely associated with water activities. However, how water activities induce sinkhole development has been explained differently, depending on the investigators' experience. So far, vacuum suction, suffusion and gas or liquid explosion have been suggested in the literature (Yuan, 1987; Chen, 1994). For any of the mechanisms to work, three elements are essential to form a sinkhole, that is, well-developed karst conduit (cave), thin overlying soil and water activity, and all three are present in many of China's mining areas.

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2. Sinkholes in karst mining areas in China

In China, karsts are developed and distributed widely in rocks which range in age from Archaeozoic to Cenozoic, but are predominantly Paleozoic. Carbonate rocks occupy an area of about 3.25 million km^2 of the country: of this bare karst is some 1.25 million km^2 and the rest is covered or buried karst (Yu, 1994). Groundwater in the karstified carbonate rocks provides local people with a very good water supply source. Unfortunately, many mineral deposits such as coal, iron, lead and zinc, gold, aluminum and copper are located in between, or above, or below the karst aquifers. As drainage of the karst water is essential for mine safety, they are often referred to as karst water-impregnated deposits. The majority of the well-known deposits with large quantities of water (mine drainage over 1 $m^3 s^{-1}$) are karst water-impregnated deposits, and it is in those mines that sinkholes frequently take place.

According to incomplete statistics, 797 regions with a total of 30 005 sinkholes have been found in 23 provinces in China. A total of 29 165 sinkholes are in parts of South China such as Guangxi, Hunan, Jiangxi, Guangdong, Yunnan, Hubei, etc. and 840 in parts of North China such as Hebei, Anhui, Shandong, Shanxi, etc. Among the sinkholes, those caused by pumping, dewatering, drainage and water inflow in karst water-impregnated deposits are large, numerous and of long duration. Up to now, 94 mining areas, mainly Paleozoic coalfields and intrusive contact–polymetallic mining areas, have reported incidents of surface collapse. Most of them are in carbonate rocks of the Ordovician, Middle Devonian, Carboniferous, Permian and Lower Triassic ages. Five mines have been abandoned or have reduced production due to the problems of sinkholes. In 25 investigated mining areas in South China, over 23 513 surface collapses were found. More than 6100 surface collapses were found in the Enkou mining area of Hunan Province in an area of 25 km^2. Some 800 surface collapses were developed within an area of 100 m^2. As the karst develops mainly in the Middle Ordovician limestones in North China, the scale and number of collapses are far less than those in South China. In 14 investigated mining areas, 800 surface collapses were found.

As a form of geohazard, uncontrolled surface collapse worsens the environments of mining areas, triggers the alteration of the hydrogeological and engineering geological conditions, adds to the complexity of factors in water impregnating deposits, increases the water inflow from karst aquifers, causes water and mud invasion, dries up wells, springs and surface reservoirs, causes subsidence of buildings, cuts off streams, causes injuries and deaths of man and livestock, destroys bridges, roads and railways, and threatens mine production and safety. In the Fankou area of Guangdong, 1950 surface collapses have developed with a total subsidence up to 5.5 million m^3, affecting an area of over 8.3 million m^2. Mine water gushed with 2 million m^3 of mud on one occasion. As a result, 70 000 m^2 of surface buildings have been damaged, together with over 164.7 acres of farmland and 15 km of railways. In the Enkou mine area of Hunan, surface collapses have damaged circa 1640 acres farmland, 18 300 m^2 of houses and 8 small reservoirs. In the Daguangshan mine area of Hubei, surface collapses caused the destruction of railway tunnels, the upending of high voltage poles, electric power outages and the flooding of mines.

A sinkhole provides a potential path for surface water and groundwater to enter a mine. The drainage area exposed within a sinkhole considerably exceeds the drainage area of the physically mined openings. Surface water bodies (rivers, lakes and ponds) can contribute to mine flow via sinkholes. Substantial costs were incurred at many mining projects in stream relocation, impermeabilization, remediation of sinkholes, and increased pumping of water from the mines. For example, in the Siding mine area of Guangxi, within an area of 1 km^2 600 collapses occurred due to lowering of the water table. On 14 May 1976; 7 June 1977; and 29 March 1979, river water flowed into the mine at up to 24 $m^3 s^{-1}$ through sinkholes in the river bed, flooding the mine three times. In Fankou Mine, recharge of river water into the mine through collapses in the river bed caused the mine drainage to increase from 0.37 to 0.78 $m^3 s^{-1}$. Surface collapses cause soil erosion as well. In the Meitanba Mine, over 2000 collapses

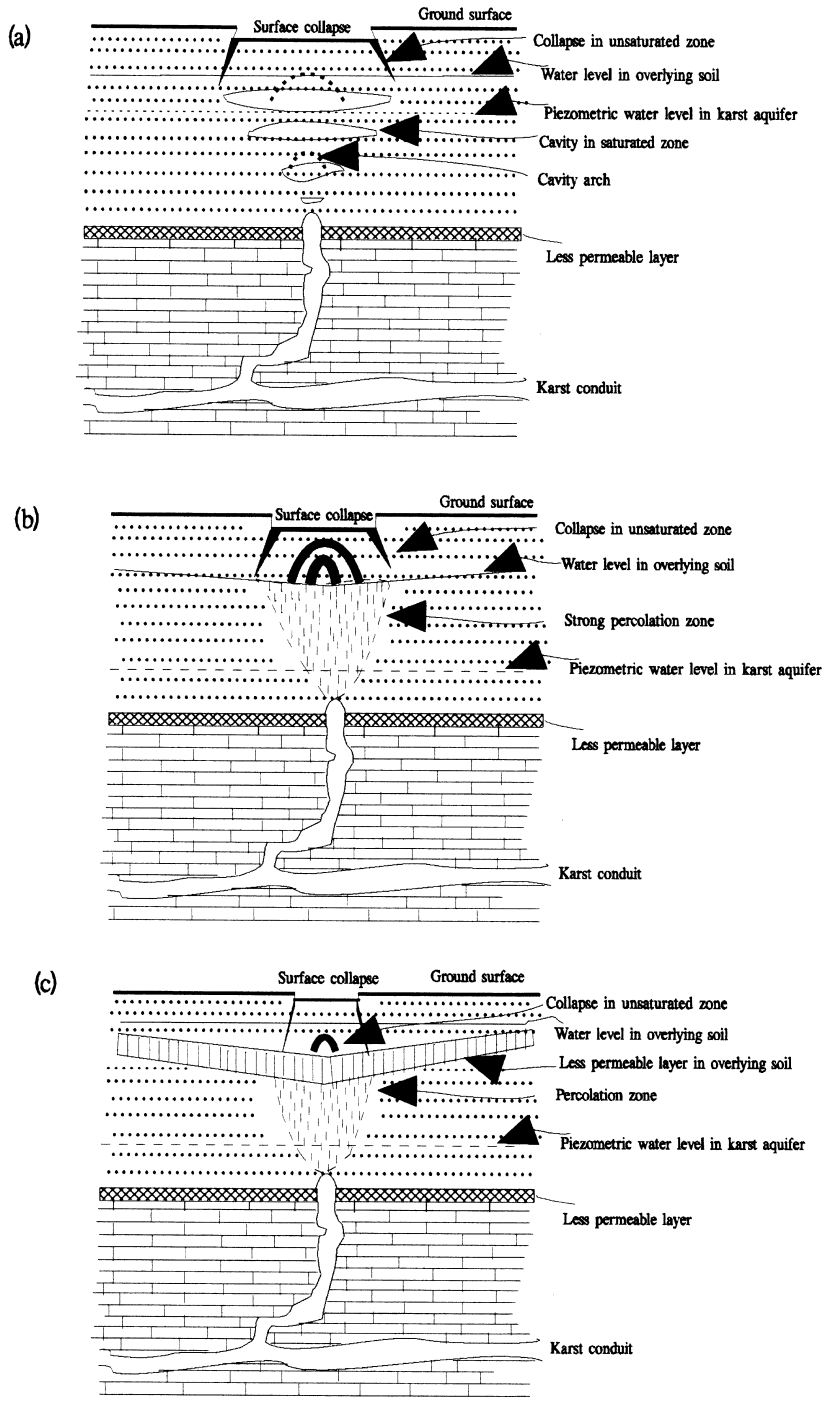

Fig. 1. Scenarios where sinkholes can be developed in karst mining areas.

have caused entries of water and mud 20 times. On 23 September 1980, a mud inrush of over 50 000 m^3 blocked a gallery over a length of circa 600 m, causing injuries and deaths of miners and closure of the mine.

3. Sinkhole formation in mining areas

In general, the distribution of surface collapses is mainly controlled by the development of karst. Surface collapse tends to occur in areas where the thickness of overlying soil cover is thin (generally <10 m), where shallow karst is intensely developed and in zones of runoff with heavy inflows of groundwater, or near zones of shallow rift development. In addition, surface collapse is commonly found along both sides of river valleys with a shallow groundwater table, or along river beds, swamps and troughs. The occurrence and distribution of collapse zones are often within the cone of groundwater depression of the ore area. Once groundwater level falls in karst aquifers, surface collapses usually take place abruptly. The cases of subsidence become more numerous with the increase of mine drainage, the drop in groundwater level, and the rise in hydraulic gradient. For example, in the Shaikoushan mine in Hunan, when mine drainage was 588 $m^3 h^{-1}$, 20 collapses occurred, but 202 occurred when mine drainage reached 1100 $m^3 h^{-1}$. It is generally accepted that sinkholes in mining areas are related to water activity, but the genesis and formation mechanism for sinkholes are rather complex. Fig. 1 shows three different scenarios where sinkholes can be developed. In Fig. 1(a), suffusion due to sand liquification and increased buoyancy contribute to the collapse. Cavities and temporarily stable cavity arches can be identified before reaching the surface. Flowing groundwater carries the solid particles into the connected karst conduit. Field observation indicates that the particle load is the greatest at the beginning of a pumping operation and decreases significantly with time (Fig. 2). Simple laboratory experiments confirmed this observation and suggested that it is the water level fluctuation but the water level decrease that contributes to the removal of overburden materials, as shown in Fig. 3. Intermittent dewatering practices can easily create new sinkholes.

A physical tank model (Chen, 1994) demonstrated that collapse could reach the surface regardless of the thickness of the soil if the karst conduit system was not blocked by the soil. The fact that 93% of the sinkholes occur in soils with a thickness of less than 10 m implies that conduits can be blocked temporarily and water inrushes into mines are the best way to remove the conduit sediments. For example, the sudden 2053 m^3 min^{-1} water inflow into the Fangezhang Mine resulted in 17 sinkholes on the surface within a couple of days. In Fig. 1(b), suffusion due to downward percolation and the increased weight of soil are the main reasons for the collapse, indicating collapses are more likely to occur during rainy seasons, as observed in other areas (Currin and Barfus, 1989). In Fig. 1(c), vacuum suction and downward percolation may be the main contributors to the collapse, which has been fully illustrated by the experiments conducted by Xu

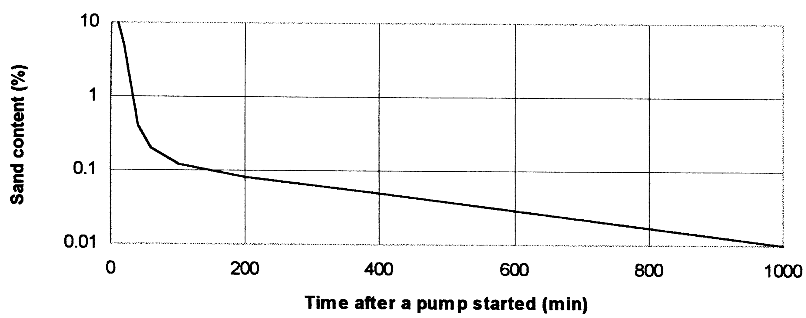

Fig. 2. Field observation of sand content in pumped water.

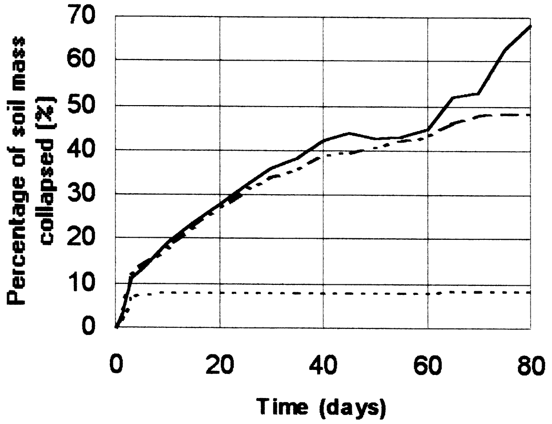

Fig. 3. Effect of water level fluctuation on suffosional process in soil samples. - - - Water level remains the same; – • • – water level fluctuates once a day; — water level fluctuates twice a day.

and Zhao (1988). The effects of vacuum suction in karst conduits on the formation of sinkholes have been theoretically explained by Zhou (1997b).

4. Prevention and remediation of sinkholes

Usually, there are warnings before a surface collapse occurs, even though it is difficult to predict accurately the occurrence of collapse. The comprehensive analysis of the geological conditions and qualitative prediction are still the basic methods. In order to determine the likely collapse locations, the investigation of subsurface cavities and karst conduits in mining areas is essential, using remote sensing techniques, geophysical methods and geological investigations. In order to prevent surface collapses in karst water-impregnated ore deposits, the key measures, as discussed above, are to control the intensity of mine drainage, to reduce water level fluctuation frequency, to seal off the karst conduit, and to reduce the vacuum level within the subsurface cavities. Gas injection into cavities has been used in some mines to avoid vacuum suction. Sinkholes stopped developing for a period of time, but when the drainage recommenced, sinkholes began to develop again. Locating the karst conduits and the subsurface cavities are critical for this method but in practice it is very difficult to detect them with the required accuracy.

The heterogeneous characteristics of karst systems provide an opportunity to reduce mine drainage intensity. Permeability of karst aquifers often reduces with depth. In the deeper part of the aquifer, downward seepage is limited due to the low permeability. Water drainage in the deeper part of the aquifer can hardly affect the water level in the upper part. During the course of dewatering, two different water levels in the same karst aquifer may coexist. Up to 200 m difference in water level between the deeper part and upper part of a karst aquifer has been found in some mines. This phenomenon makes it possible to drain water only in the deeper part of the aquifer and keep the water level at the upper part untouched so that no sinkholes can develop. As shown in Fig. 4, two major hydrogeological units can be distinguished in the Ordovician limestone. Unit I refers to the upper part of the aquifer, which has higher permeability and unit II refers to the deeper part of the aquifer, which has a permeability ten times less than that at the upper part. Multi-packer water injection tests indicated that the permeability in the zone 70 m above the ore deposit is very low. A drainage tunnel was excavated directly into the deeper part of the aquifer, the average water flow rate was only 693 m^3 day^{-1}. The water level at the

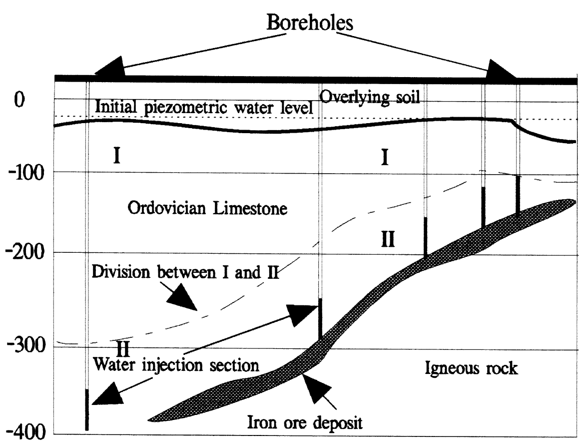

Fig. 4. Sinkhole prevention by draining water at the lower part of the karst aquifer in a mine.

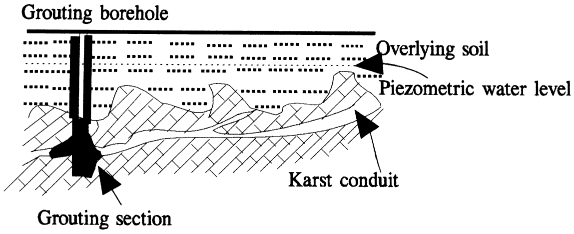

Fig. 5. Sinkhole prevention by high pressure jet grouting technique.

upper part did not change, and no sinkholes have ever been recorded in this mine.

Sealing karst conduits is another means to reduce water drainage intensity and suffusion. Fig. 5 shows an example of using the high pressure jet grouting technique to treat subsurface cavities and karst conduits. From a long-term point of view, grouting the cavities and conduits is an effective way to avoid sinkholes. However, grouting a karst aquifer involves a series of special techniques and the cost for the grouting operation may be very high (Li and Zhou, 1989). In order to avoid sudden water level changes, advanced detection is necessary in underground mines so that any potential water invasion (inflow) points are sealed in time. Mining with water pressure is another effective way to control mine water drainage (Zhou, 1997a).

As the collapses reach the surface, the measures such as backfilling and covering collapsed holes, intercepting streams and diversion of river channels should be taken in order to reduce the rate of groundwater inflow to mines through collapses. In the Enkou mine area, for example, grouting screens to cut off karst groundwater flows through integrated runoff zones, cementing channels and the alteration of stream paths have been adopted and proved to be effective in both reducing the groundwater inflow to mines through collapsed holes and controlling the development of further collapses.

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