The formation of sinkholes in karst mining areas in China and some methods of prevention

Zhou Wanfang

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 mine safety. The origin of such sinkholes is analyzed quantitatively in this paper and a combination of factors including soil weight, buoyancy, suffosion process and vacuum suction can contribute to surface subsidence. 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 to increase gas pressure in the karst conduits.

Key words Sinkholes · Karst water · Mines · China

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 cavities induce sinkhole development has been explained differently, depending on the investigators' experience. So far, vacuum suction, suffosion 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, i.e., 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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Sinkholes in karst mining areas in China

In China, karsts are developed and distributed widely, ranging in age from Archaeozoic to Cenozoic, but are predominantly Paleozoic. Carbonate rocks form the bedrock for about 3.25 million km^2 of the country: of this, bare karst is some 1.25 million km^2 and the rest are covered or buried karsts (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) 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. In South China there are 29,165 sinkholes such as Guangxi, Hunan, Jiangxi, Guangdong, Yunnan, Hubei, etc., and 840 in 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 Ordovician, Middle De-

Table 1
Surface collapse data in karst water-impregnated mining areas in China

Kast water-impregnated deposit areas	Number of collapses	Maximum dimension			Aquifer age	Brief description
		Length (m)	Width (m)	Depth (m)		
South China						
Enkou coal mine, Hunan	6100	40		30	Lower Permian	From 1972 to 1986, over 500 collapses occurred within 0.1 km^2, destroying 6.33 km^2 of farmland and 8 reservoirs. The maximum recharge from a river into the mine through collapses was up to 8165 m^3/hour.
Doulishan coal mine, Hunan	2200				Lower Permian	Most of the collapses occurred over the period of 1967–1983. Four people died and the mine drainage increased 2.5 times. The diameter of the cone of depressions is about 40 km.
Meitanba coal mine, Human	>2200	80			Lower Permian	The collapse has caused interruption of the adjacent highway. The mine water and mud increased significantly. The diameter of the cone of depression is about 10 km.
Qiaotouhe coal mine, Hunan	530				Lower Permian	The collapses destroyed the nearby railway, farmland and 3 reservoirs. The mine water drainage increased 2–3 times. The diameter of the cone of depression is 30 km.
Yijiaquiao coal mine, Hunan	100				Middle-Upper Carboniferous	The collapses were caused by mine water drainage.
Shuikoushan L-Z mine, Hunan	850	80	60	30	Permian	The thickness of the overlying soil ranges from 0 to 20 m for the collapses during 1959–1979, destroying 0.35 km^2 farmland, 6643 m^2 houses. A significant amount of river water flowed into the mines through collapses.
Chenxi coal Mine, Hunan	> 200					The collapses occurred during 1971 to 1973 with a mine drainage of 100 m^3/hour. The thickness of the overlying soils is 5–10 m.
Hongyuan mine, Hunan	314					The collapses mainly occurred during 1966–1972.
Xiaobofang copper mine, Hunan	1	80		30		It occurred on December 28, 1975. It was caused by a water inrush.
Liaoshao coal mine, Hunan	7290					The collapses were caused by mine drainage.
Fankou L-Z mine, Guangdong	1950	44		>30	Middle-Upper Carboniferous	The collapses during 1963–1985 destroyed 0.67 km^3 farmland, 68600 m^2 houses were evacuated, 4 km railway and 1.5 km highway were abandoned. The amount of water and mud flowing into the mine increased. The thickness of the overyling deposits is from 10 to 20 m.

Table 1
(Continued)

Kast water-impregnated deposit areas	Number of collapses	Maximum dimension			Aquifer age	Brief description
		Length (m)	Width (m)	Depth (m)		
Shilu copper mine, Guangdong	3176	100			Middle Carboniferous	The collapses during 1970–1983 destroyed 0.33 km^2 farmland, 20 000 m^2 houses were evacuated. The thickness of the overyling soil is from 10 to 20 m.
Makou brasses, Guangdong	>3000	45	45	42	Devonian and Lower Carboniferous	The thickness of the overyling soil ranges from 4 to 25 m, mainly clay with sands and gravel. The collapses were caused by mine drainage.
Zhangken troilite, Guangdong	90				Devonian	
Heishigang pyrite, Guangdong	2280	43	45	42	Devonian, Carboniferous	The thickness of the overyling soil is from 2 to 9 m, consisting of clay, sands and gravel. The collapses were caused by mine drainage.
Siding L-Z mine, Guangxi	> 600				Upper Devonian	The collapses during 1958–1981 forced the Siding village to be abandoned. River water invaded the mine 3 times. The thickness of the overyling deposits is from 2 to 7 meters.
Heshan coal mine, Guangxi	200	36			Lower Permian	The thickness of the overyling soil is less than 3 meters.
Xiwan coal mine, Guangxi	118	35	35	10	Carboniferous, Permian	The collapses occurred mainly before 1984. The mine was flooded several times. The thickness of the overyling deposits is less than 10 m.
Tongmengshan copper mine, Hubei	258	60	40	8	Triassic	The collapses occurred during 1964–1984, destroying a bridge, increasing the mine drainage 3233 m^3/day.
Yehuaxiang copper mine, Hubei	170	>10		>10	Carboniferous, Permian, Triassic	The collapses occurred during 1970–1977. Due to the river water intrush into the mine, the mine was abandoned.
Houzidong coal mine, Hubei	> 100	5		3	Middle Carboniferous, Permian	
Shuangqui coal mine, Hubei	100				Middle Carboniferous	
Daguangshan iron mine, Hubei	77					The collapses began at March of 1978. The reailway, highway and 4000 m^2 of houses were destroyed. Coal production was reduced.
Chengchao iron mine	10					The collapses were caused by water inrush in the tunnels.
Yuhuasi iron mine	> 10					The collapses were caused by water inrush in the tunnels.

Table 1
(Continued)

Kast water-impregnated deposit areas	Number of collapses	Maximum dimension			Aquifer age	Brief description
		Length (m)	Width (m)	Depth (m)		
Yunzhuang coal mine, Jiangxi	202					The collapses started after 1973 at a drainage of 660 m^3/hour. The overyling soil is 2–30 m thick.
Huating manganese mine, Jiangxi	89					The collapses occurred during 1960–1972, interrupting a highway and destroying farmland.
Qiaotouqiou coal mine, Jiangxi	231					The collapses ocurred during 1972–1979, destroying farmland and causing the evacuation of 22 279 m^2 houses. The mine drianage was 248 m^3/hour.
Yongshan coal mine, Jiangxi	189				Tertiary	The thickness of the overlying deposits is 5–7 meters.
Mingshan coal mine, Jiangxi	109				Permian and Tertiary	The thickness of the overyling soil is 10 m. The collapses were caused by dewatering in the limestone and dolomite.
Lehua manganese	102					The collapses were caused by dewatering in the limestone.
Fengcheng mine, Jiangxi	1					The collapse was caused by water-relasing test. The collapses are in the river bed, causing river water to enter the mine.
Geijiu, Yunnan	478					The thickness of the overlying soil is 0.4 m, consisting of clay. The collapses were caused by storing water for mineral processing.
Nanjing pyrite mine, Jiangsu	1	60				The collapse was 5 meters away from a railway. The mine was abandoned.
North China						
Yezhuang iron mine, Shandong	26	53		6	Middle Ordovician	
Gujiatai iron mine, Shandong	18				Middle Ordovician	
Xigang coal mine, Shandong	2				Carboniferous	
Datong coal mine, Shanxi	2				Ordovician	
Lier coal mine, Anhui	6				Ordovician	
Xieyi coal mine, Anhui	9	30			Ordovician	
Kongji coal mine, Anhui	6	39			Upper Carboniferous	
Tongguanshan copper mine, Anhui	100	30	30	> 30	Carboniferous, Permian	The collapses were caused by dewatering in the limestone.
Xiquiao coal mine, Anhui	200				Middle Ordovician	

Table 1
(Continued)

Kast water-impregnated deposit areas	Number of collapses	Maximum dimension			Aquifer age	Brief description
		Length (m)	Width (m)	Depth (m)		
Fangezhuang coal mine, Hebei	17	27.5		12	Middle Ordovician	The collapses were caused by a water inrush incident in 1984.
Xibeiping coal mine, Hebei	2				Middle Ordovician	
Linxi coal mine, Hebei	2	12		15		
Weijacun zillerite mine, Liaoning	20	15		8		
Fuzhouwan clystone mine	8				Middle Ordovician	
Tonghua mine, Jilin	1	80	50	15		The collapse was caused by water inrush.

vonian, 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 6,100 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. Since karst develops mainly in the Middle Ordovician limestones in North China, the scale and number of collapses are far less than those found in South China. In 14 investigated mining areas, 800 surface collapses were found. Table 1 lists the surface collapses in some of the karst water-impregnated deposits.

As a form of geological hazard, 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, as listed in Table 1. In the Fankou area of Guangdong, 1,950 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. 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 about 1,640 acres of 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 cuts 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 waterbodies (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 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 m^3/s to 0.78 m^3/s. Surface collapses cause soil erosion. In the Meitanba Mine, over 2,000 collapses have caused entries of water and mud on 20 occasions. On 23 September 1980, a mud inflow of over 50,000 m^3 blocked the gallery over a length of more than 600 m, causing injuries and deaths of miners and closure of the mine.

Sinkhole formation in mining areas

In general, the distribution of surface collapses is mainly controlled by the development of karst. Surface collapse

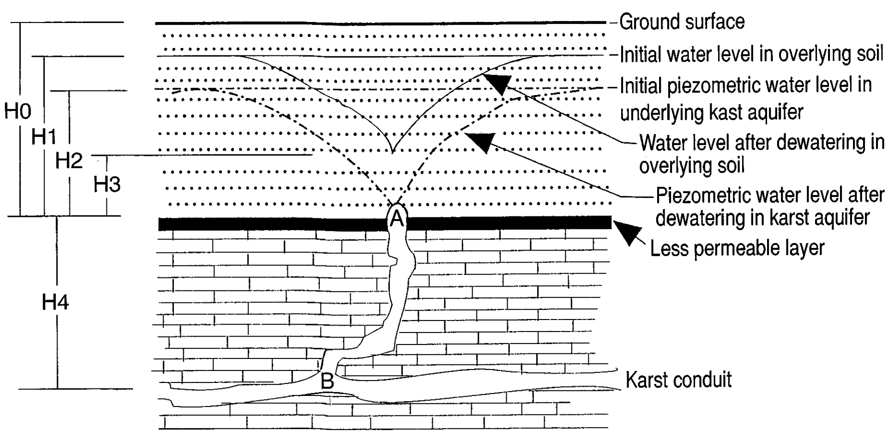

Fig. 1
Mechanical analysis of surface collapse in mining areas

tend to occur in areas where the thickness of overlying soil cover is thin (generally less than 15 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 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 increasing mine drainage, a drop in groundwater level, and a rise in hydraulic gradient. For example, in the Shaikoushan mine in Hunan, when mine drainage was 588 m^3/h, 20 collapses occurred, but 202 occurred when mine drainage reached 1,100 m^3/h. It is generally accepted that sinkholes in mining areas are related to water activity, but the genesis and formation mechanism for sinkholes is rather complex. Finding the principal cause of collapse is of great importance so as to eliminate or reduce the possibility of collapse occurrence and development.

Figure 1 illustrates the relevant factors affecting surface collapses. It consists of overburden soil, and underlying karst conduit system containing groundwater. A less permeable layer is shown representing the weathering zone of the limestone, which is often present in karst mining areas of China. In some areas, the less permeable layer may not exist, thus the piezometric water level in the karst aquifer equals zero. Initially, there is no water flow and the soil particles are stable, the pressure imposed on the solid particles of the overburden soil at point A can be expressed as:

$$P_A = (H0-H1)\gamma_{s,u} + H1\gamma_{s,s} - H1\gamma_w - H2\gamma_w + P_a, \quad (1)$$

where P_A is the pressure on solid particles at point A, H0 is the thickness of the overburden soil, H1 is the initial water level in soil, H2 is the initial piezometric water level in karst aquifer, P_a is the atmospheric pressure, $\gamma_{s,u}$ is the soil density in unsaturated zone, $\gamma_{s,s}$ is the soil density in saturated zone, and γ_w is the density of water.

After dewatering in the karst aquifer or a sudden water inflow into the mine, the piezometric water level falls to point A, the water level in the soil is assumed to drop as well. Correspondingly, the pressure at point A changes to:

$$P_A = (H0-H3)\gamma_{s,u} + H3\gamma_{s,s} - H3\gamma_w - [P_{B,w} + (B_B{}^2 - V_A{}^2)/(2g)\gamma_w] + H4\gamma_w + P_a, \quad (2)$$

where H3 is the water level after dewatering in the overlying soil, $P_{B,w}$ is the water pressure at point B in the karst conduit, $V_B{}^2$ is the water flow velocity at point B in the karst conduit, $V_A{}^2$ is the water flow velocity at point A in the karst conduit, g is the gravitational acceleration, and H4 is the height difference between points A and B.

Then the pressure difference can be calculated by:

$$\Delta P = P_A - P_A = (H1-H3)(\gamma_{s,u} - \gamma_{s,s}) + (H1-H3)\gamma_w + H2\gamma_w - \gamma_{s,u} + H1\gamma_{s,s} - H1\gamma_w - H2\gamma_w - [P_{B,w} + (V_B{}^2 - V_A{}^2)/(2g)\gamma_w] + H4\gamma_w, \quad (3)$$

where $(H1-H3)(\gamma_{s,u}-\gamma_{s,s})$ represents the effect of the dead weight of soil. As the density of soil with water is greater than the density of dry soil, the weight of soil above point A decreases with a drop in water level, while the weight of soil increases when the water level rises. $(H1-H3)\gamma_w$ represents the effect of buoyancy in the soil. As the water level falls the soil particles tend to lose their upward support from the water. A certain drawdown of groundwater level causes a fixed decrease of buoyancy, but the same decrease of buoyancy has a different effect on soil masses of different thicknesses. Its effect varies inversely with the thickness. $H2\gamma_w$ represents the effect of buoyancy caused by the water in the karst conduit system. In most cases where dewatering has proceeded for a long time and a sinkhole may form, $H2 = 0$, thus the buoyancy force imposed by the karst water is negligible.

In Eq 3, $P_{B,w} + (V_B{}^2 - V_A{}^2)/(2g)\gamma_w$ represents the effect of water flow in the karst conduit system. It also shows the ability of water to erode and carry solid particles. Higher velocity at point B will have stronger erosion ability and carry more materials away. If point B represents the discharge point, then $P_{B,w} + V_B{}^2/(2g)\gamma_w = P_a$. The velocity at point A will determine the erosion and transport capacity of the water. As the dewatering process continues, the velocities at points A and B approach the same value and then suffosion will stop. It is obvious that erosion and transport of soil particles mostly takes place when the water level fluctuates. This is supported by the fact that water has high turbidity whenever the pump is started and becomes clear as the pumping continues. Figure 2 shows the effect of water fluctuation on suffosion from an experiment using soil samples of 5 cm by 5 cm by 5 cm. The more frequent fluctuation in water level caused a greater amount of soil collapse, implying a stronger suffosion process. When the water level kept constant, the soil mass became stable, 4 days after the soil sample was put into the water.

In Eq 3, $H4\gamma_w$ is the static water pressure between points A and B. As shown in Fig. 3, if B is assumed to be the discharge point, then $H4\gamma_w = P_a - P_g$, where P_g is the air pressure at point A but inside the karst conduit system, which equals the air pressure inside the U-shaped tube, P_0. Thus, $H4\gamma_w = P_a - P_o$, which is actually the vacuum pressure inside the karst conduit. This vacuum suction process may take place when the water level in the underlying cavity is changing from a confined state into a semi-filled state. Some experiments and field observations suggest that this may be true when the overlying soil is sufficiently stiff and the cavity wall is air-tight or the water-level drawdown is sufficiently rapid. Field tests have shown that the vacuum level is closely related to water content within the soil (Fig. 4). The maximum vacuum suction occurs at the beginning of a dewatering process. As the dewatering process continues, the water content decreases as does the vacuum suction force.

The above analyses indicate that sinkholes in karst mining areas are caused not by a single force but by a combination of different forces including soil weight, buoyancy, suffosion, and vacuum suction. One or two factors may be dominant for a specific collapse, depending on the hydrogeological conditions. Figure 5 shows three different scenarios where sinkholes can be developed. In Fig. 5a, suffosion due to sand liquification and increased buoyancy contribute to the collapse. Cavities and temporarily stable cavity arches can be identified before reaching the surface. In Fig. 5b, suffosion due to downward percolation and the increased weight of soil are the main reasons for the collapse. In Fig. 5c, vacuum suction and downward percolation may be the main contributors to the collapse.

It should be pointed out that the thickness of the overburden soil does not seem to be an important factor affecting sinkhole formation. In fact, 93% of the sinkholes occurred in soils with a thickness of less than 10 m. Only 1.8% sinkholes occurred in soils with a thickness of more than 15 m. This phenomenon can be well explained by a physical tank model (Chen 1994). Physical simulations from the model 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. Every time when the conduit was blocked, collapse stopped temporarily and the collapse would continue when the filling soil was removed. Although the thickness does not determine whether a collapse takes place or not, it may affect the openness of the karst conduit system, the

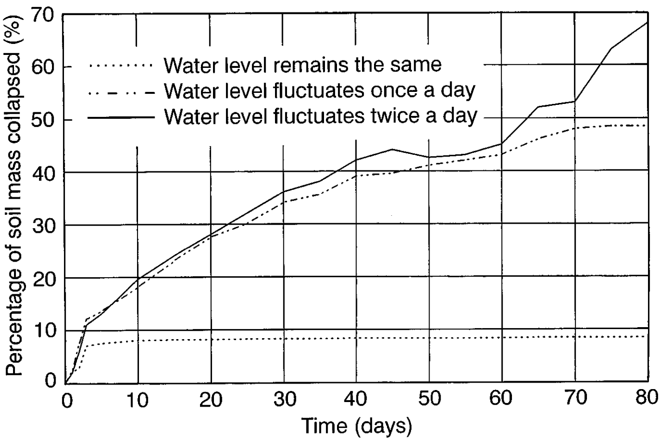

Fig. 2
Effect of water-level fluctuation on suffosion in soil samples

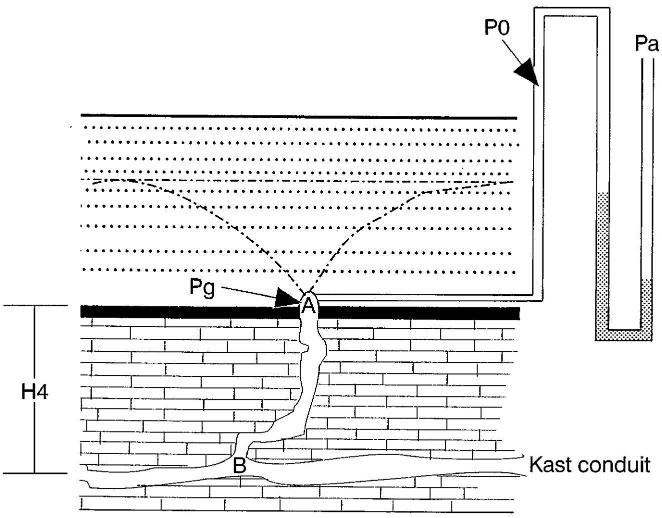

Fig. 3
Formation of vacuum pressure during dewatering process

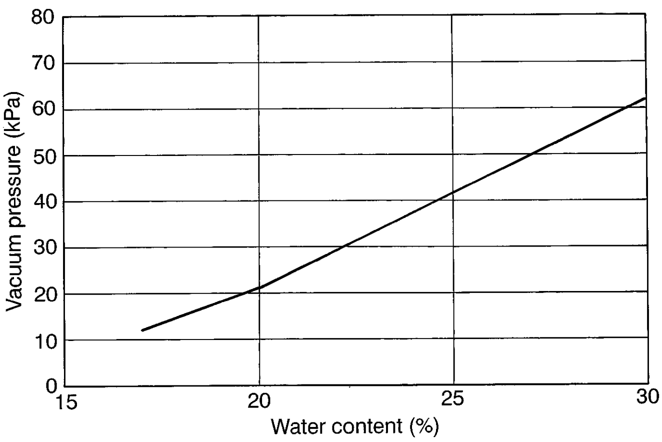

Fig. 4
Vacuum level vs water content

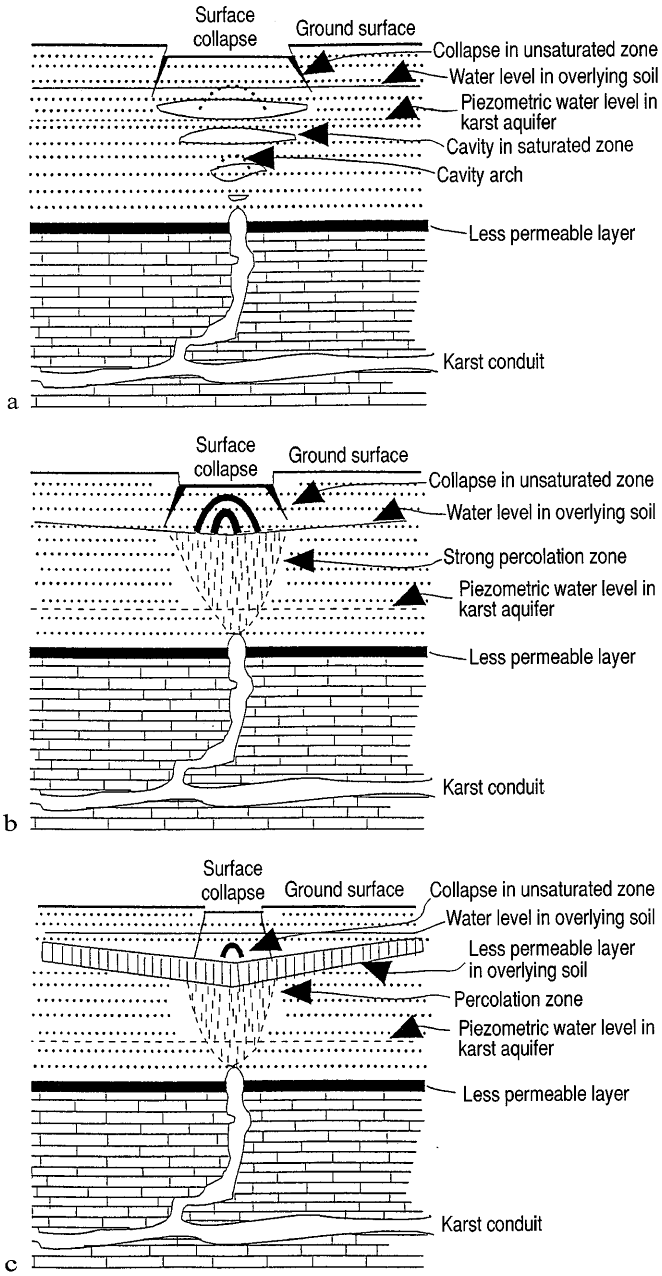

Fig. 5a–c
Surface collapse processes for different scenarios. **a** upward water flow, **b** downward water flow, **c** downward water flow with a less permeable layer in the soil

efficiency of the conduit to remove soil particles, and thus the time for a collapse to reach the surface.

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 decreases 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 co-exist. 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. 6, 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 10 times less than that of 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. The water level at the 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 suffosion. Figure 7 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 1996).

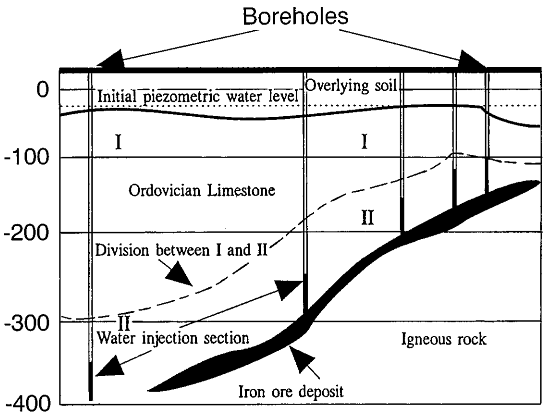

Fig. 6
Sinkhole prevention by draining water at the deeper part of the karst aquifer

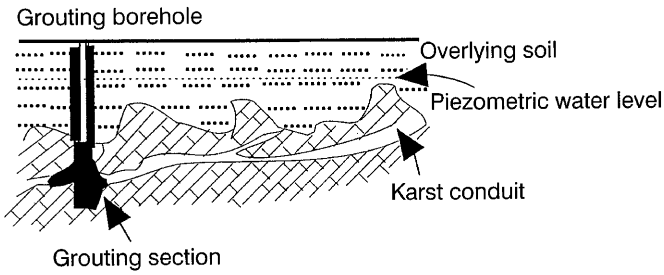

Fig. 7
Sinkhole prevention by using high-pressure jet grouting technique

As the collapses reach the surface, 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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