Advances in Karst Science

Xiaozhen Jiang · Mingtang Lei · Wanfang Zhou ·
Fubiao Zhou · Xiao Ma · Jianling Dai · Zongyuan Pan

Monitoring and Early Warning Technologies on Karst Lands

Surface Collapse and Groundwater Contamination

Springer

Advances in Karst Science

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Foreword

The phrase "expect the unexpected" is often associated with engineering construction and environmental remediation in karst terranes. This is because karst does not follow the typical rules that we learnt from most landscapes that form, as the rain, rivers, wind, waves, and even glaciers break down and wear away the rocks. This isn't the case with karst terranes. Karst developed on such rocks as limestone, dolomite, gypsum, or halite that simply dissolve in contact with acidic water, leaving little behind except insoluble leftovers. The solution process occurs both on the ground surface and in the subsurface, resulting in karst features characterized with depressions on the bedrock surface, a highly irregular bedrock surface, an underground tributary network of solution-widened conduits and small tubules that may merge into small and large caves. These karst features tend to establish an underground circulation in which the water sinks into the ground rather than flowing away in rivers and discharges through karst springs or other outlets.

The bedrock solution process can lead to cave collapses on a geological timescale. But on a human timescale, the most intimately tied to karst terranes are soil collapses in areas where the bedrock is buried beneath an overburden made up of alluvial, glacial, or marine deposits or the insoluble leftovers from the bedrock dissolution. The downward drainage into voids in the bedrock carries the overburden sediment down with it. The sediment is eroded from the bottom upwards giving no sign of the ongoing erosion, or of the impending collapse at the ground surface. When the ground sinks suddenly, small, or not-so-small depressions, often referred to as "karst collapses", suddenly appear in your construction site. They sink down 1, 2, 3, or more meters, and they wreak havoc with your plans for a foundation. This same erosion process can occur slowly, even imperceptibly, just a couple of centimeters or less per year. A noticeable shallow depression can eventually form on the ground surface in 25 years. If this process develops under the foundation of a building, major cracks occur, and the building becomes unlivable.

The scale and rate of this karst collapse process is variable. The same process that produced those small karst collapses on your site, under the right circumstances, and on a grander scale, can bring about gigantic collapses that damage roads, houses, or buildings. When the karst is covered, karst identification during subsurface exploration programs is challenging, and it is difficult to anticipate when and where these collapses will occur.

Also difficult is the monitoring of groundwater flow and the associated contaminant transport in a network of discrete channels hidden underground. So, unless the monitoring well actually intercepts a conduit in the network, it will not receive drainage and detect contamination. However, the main question is, how do we hit a conduit in the first place? Since this drainage network is under the ground, nature does not provide any "as builts" for us to review. If the water is flowing rapidly through a discrete conduit in the rock, possibly in the order of a foot wide, the chances for the monitoring well to intercept it is small.

Monitoring of springs has been considered a viable option since the entire drainage network eventually discharges at springs. The spring discharge will integrate flow from the entire basin, including any contamination that is occurring. Unfortunately, it is still not that easy; it never is in karst. Contaminant generally moves through the drainage network in flood pulses. Samples taken at low flow may be clean, while a precipitation-generated peak discharge may be highly contaminated. So, simply sampling at the spring on a quarterly basis will not do it. And it is equally important to be sure to prove it is the right spring, usually by dye tracing. Underground drainage networks have been known to cross each other and even to flow under surface streams without any interconnection.

Fortunately, there are some solutions to these challenges. We now understand that karst follows its own rules. Data on the karst collapse mechanisms and groundwater dynamics have been collected in recent years to understand these rules of karst formation. In addition to specialized techniques that have been developed for site characterization, innovative methods, and tools have been evaluated and validated for monitoring and early warning of the geohazards. I have known the lead authors of this book for three decades, and their expertise is on karst collapse formation, prevention, and mitigation. I am honored to write the foreword for this book, which summarize these innovative monitoring and early warning technologies, and to present case studies on their applications to solving practical problems for either karst collapses or groundwater contamination.

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Contents

About the Lead Author

Dr. Xiaozhen Jiang is a professor at the Institute of Karst Geology, Chinese Academy of Geological Sciences, and a senior researcher at the UNESCO International Karst Research Center. She serves as the deputy director of the Karst Exploration Technology Professional Committee of the Chinese Society for Rock Mechanics and Engineering and on the National Natural Resources and Territory Spatial Planning Committee of China (SAC/TC93/SC2) and the Karst Professional Committee of the Geological Society of China. She is an appointed technical expert by the Ministry of Natural Resources on geological disaster prevention and control.

Dr. Jiang has long been committed to the research of karst collapse prevention and control technology. As the principal investigator, she has successfully completed more than 40 projects sponsored by the National Natural Science Foundation, the Ministry of Natural Resources, and industrial enterprises. Based on over 20 years' field studies and extensive research with large-scale physical analog models, she proposed the sudden changes in water and gas pressure as the collapse mechanism in karst systems, developed criteria determination methods, and established a technical support system for karst collapse monitoring and early warning, early identification, and dynamic risk assessment. She pioneered the application of distributed optical fiber sensing to karst collapse monitoring and developed a cloud-based information management platform by integrating data from dynamic monitoring and ground penetration radar.

She has published more than 40 papers and 10 invention patents. She serves as the editor-in-chief for the industry standards on "Karst Collapse Monitoring Specifications" and "Karst Ground Collapse Prevention and Control Engineering Exploration Specifications" and is the lead author of the monographs "Karst Collapse Monitoring Technology" and "Atlas of Karst Collapses". The newly developed technologies have been applied to karst collapse monitoring along several railways including the Wuhan-Guangzhou High-speed Railway and Guiyang-Guangzhou High-speed Railway as wells as to collapse-prone provinces of China such as Guangdong, Guangxi, Hunan, Hubei, Anhui, Guizhou, Chongqing, and Shandong.

1

Vulnerability of Karst Terranes to Ground Collapses and Groundwater Contamination

1.1 Hydrodynamics of Karst Terranes

Recharge and groundwater flow characteristics are the primary factors that make karst terranes vulnerable to surface collapse and contamination. One-dimensional channels, two-dimensional planar partings such as fractures, joints, and faults, and three-dimensional inter-granular matrix pores constitute porosities for groundwater storage and flow in a karst aquifer. While rapid and possibly turbulent flow occurs in large channels, commonly termed conduits, or caves if they are accessible by people, slow and laminar flow occurs in the rock matrices and tight fractures. While the majority of the undergroundwater flows through the conduits in many karst aquifers, the conduits actually contain only a small fraction of the total volume of water in the aquifer. The chance for a randomly selected well to intercept a major conduit is small. Because groundwater levels in monitoring wells installed in different porosities respond differently to recharge events, it should be cautious to interpret the groundwater flow direction from water level measurements in monitoring wells, especially on local scales. Specialized techniques such as tracer tests or geophysics may be needed to determine the groundwater flow paths. In non-karstic terranes, there is a clean distinction between surface water and groundwater, and between surface drainage basins and groundwater aquifers. Drainage basins, which determine the catchment and runoff characteristics of surface water are defined by drainage divides set by local topography. Surface water is often only loosely coupled to groundwater systems because of the slow rate of infiltration. These conceptual distinctions between basins and aquifers are blurred in karst areas because of the integrated system of solution-enlarged fractures or conduits that carry water through the subsurface. Localized recharge to the conduit system occurs where surface streams flow underground and where sinkholes collect overland flow and direct to the subsurface. The discharge of water from the conduit system often takes place at one or several large springs that form the headwaters of a perennial surface stream. There is in karst a much more intimate relationship between groundwater and local surface water than in other types of aquifers.

1.1.1 Recharge Types

In karst terranes, the recharge includes inputs from surface catchments on non-karstic rocks. These non-karstic, but hydrologically connected rocks are referred to as borderland. Surface runoff from the borderlands drains through surface streams that flow onto the karst area, where some sink underground at the margin of the karst land. These are the sinking stream inputs to the karst groundwater system. Little runoff is present on the karst land, which is typical in well-developed karst terranes. Overland flow during storms disappears into sinkholes to enter the groundwater system as internal runoff. Depending on where the water has come from, the recharge sources to a karst aquifer can be divided into two categories—allogenic recharge and autogenic recharge. An allogenic recharge derives its water from a neighboring non-karst borderland, whereas an autogenic recharge derives its water from meteoric precipitation falling on the karst land.

The recharge processes are affected by the overlying soil (Lloyd et al. 1981) and the epikarst. As shown in Fig. 1.1, the epikarst consists of the upper most portion of the unsaturated rock where significant fracturing, solutional enlargement, and storage may occur. The network of dissolved fractures and bedding planes is normally filled with sediment, but it is typically more permeable than the rock matrix. Through this permeable zone, the drainage flows to a solution pipe, which directs the collected water down into the limestone. The cutters provide a myriad of entrance points into the epikarst zone and the solution pipes function as drains for the water in the perched epikarst zone. Because water flow from the surrounding epikarst zone converges toward these pipes, more limestone will be dissolved

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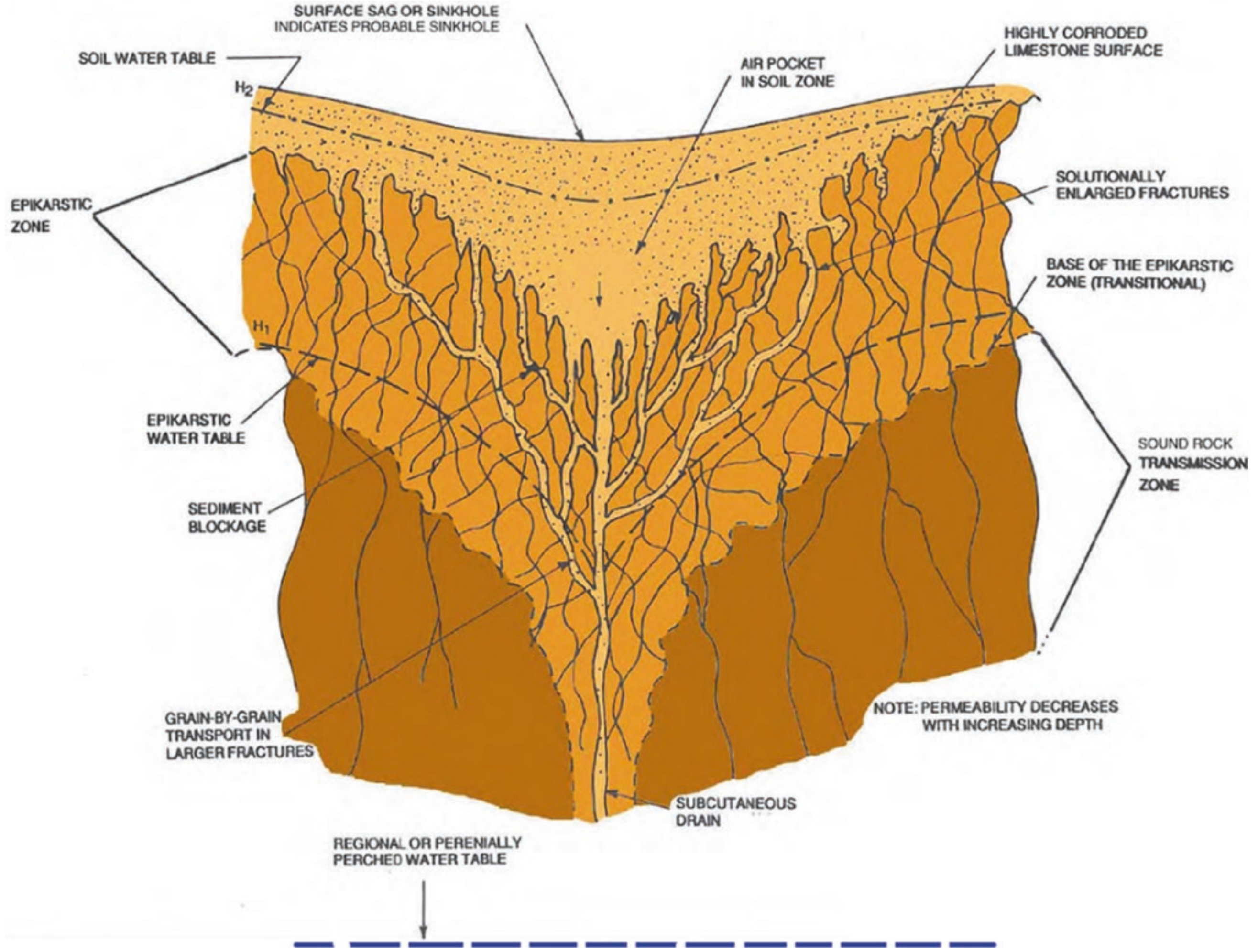


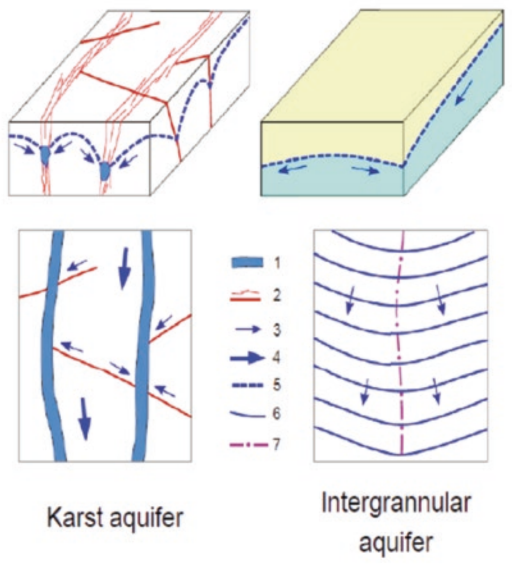
Fig. 1.1 Recharge passageways in epikarst (base map from Williams 1985) (Perching may occur in both the epikarst zone (H_1) and in the soil zone (H_2), but the flow is always directed toward a subcutaneous drain)

and removed around the pipes, thus continuing the subsurface erosion processes and the development of the broad depressions or sinkholes. Following infiltration through topsoil and internal runoff through sinkholes on the karst land, water can be collected and temporarily stored in the epikarst zone, until it subsequently joins the saturated zone. The channeling of soil water to the subcutaneous drains eventually contributes to a catastrophic collapse of the overburden (Williams, 1985).

1.1.2 Flow Characteristics

Because multiple types of porosity such as caves, conduits, fractures, and matrix pores are potentially present in a karst aquifer, the hydraulic conductivity is highly heterogeneous on the scale hierarchy. Figure 1.2 presents an example of groundwater flow patterns in a karst aquifer and compares the characteristics with a non-karst inter-granular aquifer. Groundwater flow patterns can be characterized by the co-existence of steady and unsteady flows, laminar and turbulent flows, isolated groundwater flow, and continuous groundwater flow. The groundwater flow field can be hydraulically connected to surface water and be sensitive to water recharge or extraction. Conduit flow aquifers behave hydraulically as a system of pipes with flow velocities similar to those of surface water streams, whereas diffuse flow aquifers contain solution-enlarged fractures that are relatively small and generally transmit water under laminar flow conditions.

What is generally described as the characteristics of a karst system depends very much on the type of investigation method used and on the scale of the flow domain. A detection method with a large averaging volume will produce parameter fields that appear to be almost homogeneous, whereas from small-scale measurements, the same aquifer may appear highly heterogeneous. An investigation method may be more selective in the analysis of the



Legend

1. Preferential flow path (e.g., fracture or fault zone or karst conduit/channel)
2. Fracture/fault
3. Local flow direction
4. General flow direction
5. Position of hydraulic head (water table)
6. Hydraulic head contour line
7. Groundwater divide

Fig. 1.2 Select characteristics of karst aquifers

high or low hydraulic zones. Therefore, the application of a singular method to karst investigation is not adequate to characterize a karst system. Only the combination of different methods at the core sample, borehole, intermediate scale, and catchment scale may provide a somewhat complete view of the relevant processes. Techniques such as tracer tests, cave mapping, and geophysical surveys provide important information on the conduit flow portion of a karst aquifer, while water table mapping relates to the diffuse flow portion of the karst aquifer. If conduit flow analysis is combined with a water table map of the area, anisotropic flow (the flow lines will not be orthogonal to the equipotential lines) will become evident. In fact, it is very possible that some flow lines may even run parallel to the equipotential lines. This concept appears to be contrary to conventional wisdom as to be completely ignored in many groundwater investigations in karst terranes, which can lead to devastating effects from chemical contaminant releases because the flow route is incorrectly predicted from data collected in monitoring wells. The methodology of using dye-tracing studies allows the more accurate definition of the true flow paths and connections between potential sources and receptors of contaminants (Zhou et al. 2002).

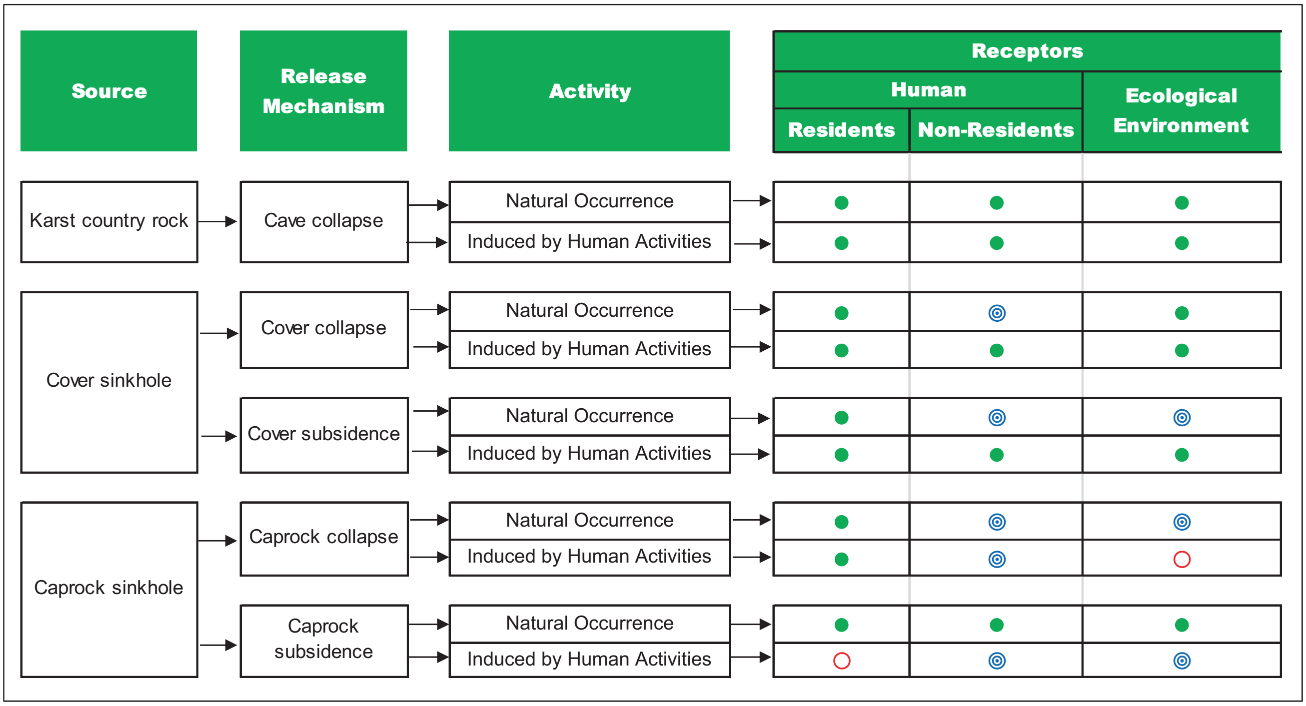
1.2 Vulnerability to Ground Collapses

Karst collapses, also known as sinkholes or dropouts, are a global geohazard and have occurred in 23 countries, including China, the United States of America (USA), Canada, South Africa, Italy, France, the United Kingdom, Germany, Russia, and Turkey. The soluble rock in China, for example, encompasses approximately 3.44 million km^2, consisting of 2.06 million km^2 of exposed and covered karst and 1.38 million km^2 of buried karst, accounting for more than a third of China's land area. China is one of few countries possessing every type of karst, whereas karst collapse is a unique geological feature. Based on the karst inventory conducted in 2020, there were 3800 reported karst collapses and high-risk collapse areas totaling 1.495 million km^2. The high-risk area included the cities of Guangxi, Guizhou, Hunan, Jiangxi, Sichuan, Yunnan, Hubei, and Chongqing in south China and Hebei, Shandong, Liaoning, and other provinces in northern China. The northeast China also experienced serious karst collapse disasters. Of 337 prefecture-level cities in China, 105 cities were in high-risk karst collapse area. Approximately 2000 km of high-speed railways were constructed in collapse-prone areas, and 1800 km of high-speed railways will be constructed in collapse-prone areas. Karst collapses mainly occur in covered karst where the topography is relatively flat. With the development of urbanization, concealment and suddenness of karst collapses make them less predictable. In China, human engineering activities induced more than 75% of karst collapses. Karst collapse has become a major geological problem faced by the cities, infrastructure constructions, and natural resources exploitation in karst areas. In-depth analysis of karst collapse mechanisms and the induced geohazards is the basis and pre-requisite for monitoring and early warning of karst collapses, and for establishing geohazard control and mitigation measures in karst areas.

1.2.1 General Processes of Karst Collapses

Ground collapses result from sinkhole development processes. There is no universal theory of sinkhole development. The recommended approach is to understand the processes of sinkhole development and apply them to site-specific conditions. Although the hydrogeologic settings vary from site to site, the basic processes remain the same. Sinkholes result from two different processes: either the transport of unconsolidated overburden materials downward along solution-enlarged channels or the collapse of bedrock roofs over cavities due to progressive enlargement by solutioning. Sinkholes that involve the collapse of cover sediment are appropriately termed cover-collapse sinkholes, while sinkholes resulting from roof collapse are termed cave collapse sinkholes. Figure 1.3 shows the various karst collapse hazards.

Pre-existing dissolved voids in the underlying bedrock or soil are the most critical pre-requisite for karst collapses. Therefore, carbonate rocks such as limestone and dolomite are the major candidate geologic formations of karst collapses. Karst collapses also occur in evaporites such as gypsum and halite. Under some circumstances, collapses even occur in sandstones. The most damaging sinkholes are cover-collapse sinkholes. Figure 1.4 shows a schematic diagram of the cover-collapse sinkhole development, which includes at least three basic elements: development of karst features in the underlying bedrock, overburden layer of a certain thickness, and groundwater activity. Karst collapses often result from hydrogeologic circulations in karst water systems. Circulation of groundwater through karst is significantly different from water circulation through non-karst settings. Recharge of karst aquifers is direct through sinkholes and swallets, and by percolation of rainwater through a network of joints. Moreover, karst groundwater systems can transport sediment and contaminants virtually unimpeded into an aquifer, cave, or spring system due to the rapid recharge rate and lack of filtering. The sinkhole collapses result from internal erosions including removal of dissolved limestone by dissolution, downward transport of unconsolidated sediments, or collapse of bedrock into deeper voids, where water (precipitation, surface water, or groundwater) is the driving force in karst and sinkhole formation. Understanding water dynamics in a karst system is essential in understanding sinkhole formation mechanisms. All too often we only consider exploratory borings and geophysical methods to help characterize a project site. These methods provide valuable snapshots in time of subsurface conditions, which is important, but they provide little insight into groundwater fluctuations. Engineering over karst needs to consider groundwater monitoring programs to understand both hydraulic head fluctuations as well as



Source	Release Mechanism	Activity	Receptors		
			Human		Ecological Environment
			Residents	Non-Residents	
Karst country rock	Cave collapse	Natural Occurrence	●	●	●
		Induced by Human Activities	●	●	●
Cover sinkhole	Cover collapse	Natural Occurrence	●	◎	●
		Induced by Human Activities	●	●	●
	Cover subsidence	Natural Occurrence	●	◎	◎
		Induced by Human Activities	●	●	●
Caprock sinkhole	Caprock collapse	Natural Occurrence	●	◎	◎
		Induced by Human Activities	●	◎	○
	Caprock subsidence	Natural Occurrence	●	●	●
		Induced by Human Activities	○	◎	◎

Fig. 1.3 Karst collapses and associated hazards (Green circles represent complete pathways for damages caused by collapses; blue double-circles represent potentially complete pathways for damages caused by collapses; red circles represent incomplete pathways for damages caused by collapses. These symbols shown here are for demonstration purposes only)

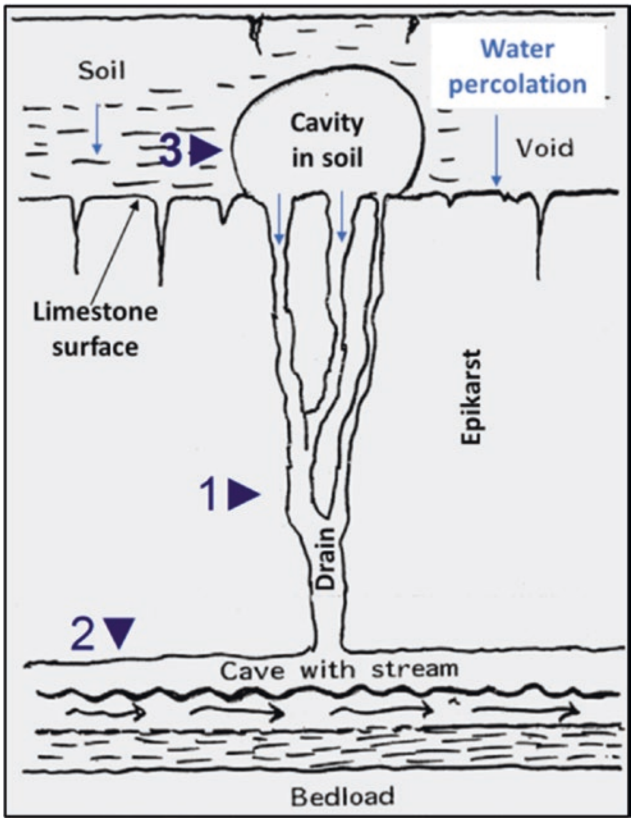


Fig. 1.4 Schematic diagram showing essential features of a cover-collapse sinkhole (modified from White 1988) (1—downward drainage "shaft" in limestone; 2—horizontal conduit system providing lateral groundwater flow and sediment transport; 3—upward stoping erosion in overburden sediment leading to sinkhole collapse)

water quality changes. In addition, remedial measures could reduce greatly, but not eliminate entirely, the probability of sinkhole occurrence or severity. Sinkhole collapse monitoring provides essential data for early warning of sinkhole occurrences. The sudden occurrence of a cover-collapse sinkhole tends to create bowl-shaped, funnel-shaped, or cylindrical depressions on the ground surface.

Sinkholes do not occur randomly. They occur only where hydrogeologic conditions have created solution-enlarged pathways in soluble rock. Solution conduits provide channels for water to move and erode cover sediment into deeper dissolved voids. Limestone within the Appalachian region generally dissolves at an approximate rate of 1–1.5 in. per 1000 years. As such and within project life cycles, limestone dissolution is in most cases not the concern except for paleo-karst cave collapses that occurred in geological history. The existing epikarst conduits play the most important role in providing pathways for overlying sediment to undergo subsurface erosion to create a sinkhole.

Years of experience suggest that the timeframe for sinkhole development is variable, sporadic, and unpredictable. Large downward water gradients or large fluctuations along the soil-rock interface are significant contributors to sinkhole development. As the soil cavity forms above the solution pipe from subsurface erosion, it may gradually enlarge upward as its roof continues to erode.

- If the sediments covering the limestone are relatively non-cohesive, the soil cavity may erode upward rapidly without growing wider. As the roof of the cavity crumbles and sediments are deposited on the floor of the cavity, the cavity may simply migrate upward without increasing in size, like a bubble rising through the liquid. For example, along the west coast of Florida where 5–10 in. of clean sand overlies the limestone, more than 100 sinkholes collapsed following a 10-inch rain event.
- More cohesive strata within the overburden may temporally impede the upward erosion, forming a temporarily stable soil arch and causing the cavity to grow laterally with slabbing and raveling failures. Cavity shape tends to correlate with soil type and often resembles an inverted teardrop with more cohesive soils developing wider cavities. As the upward progression of erosion reaches a more competent layer, the roof of the cavity may flatten out, with lateral growth continuing until the walls taper down toward the bedrock. Eventually, the upward erosion of the soil void may leave only a thin roof of sediments that are not strong enough to support their self-weight. The result is a sudden collapse. The upward collapse may develop over the years. As a result, in terrain underlain by clay over limestone, air-filled soil voids may be present for extended time periods, which provides an opportunity to detect them using geophysical techniques before they collapse.
- Cover collapse can be a repetitive process. Collapse locations are localized over epikarst drains. If a drain is plugged with sediment, erosion ceases temporarily, and the sinkhole may fill. This can be a long-term condition. For collapse to continue, sediment must be removed from the deeper voids. The timing of repeated collapse is irregular and unknown.
- Subsidence rather than collapse sometimes results in the formation of sinkholes. Movement of unconsolidated materials into the bedrock, where the overlying materials are not strong enough to maintain a cavity roof, results in a subsidence sinkhole at the surface. Damages to structures by such sinkholes are not catastrophic but cumulative.
- Extreme weather conditions and human activities may intensify the sinkhole development processes and thus shorten the timeframe of sinkhole occurrence. Human activities include intrusive investigations and engineering constructions such as drilling activities, modification of surface water drainage, groundwater pumping, grouting, and excavation may accelerate the sinkhole

development processes. Extreme weather conditions involve high levels of precipitation and rapid changing in groundwater levels.

1.2.2 Research Status of Karst Collapse Mechanisms

The seriousness of the karst collapse did not receive attention until the 1970s. In 1973 the International Association of Engineering Geology held the first international symposium on “Karst collapse and subsidence, engineering geological problems related to soluble rock” in Hannover, then West Germany. Since 1984, the multidisciplinary international symposium on “Sinkholes and their engineering and environmental impacts” has been held approximately every two years. The research on karst collapse has gradually transitioned from descriptions of karst collapse characteristics and development regularity to investigation and exploration of geological conditions, risk assessment, and risk management.

The study of karst collapse in China can be divided into four periods. Before the 1980s, sporadic research was conducted on karst collapse induced by mining operations in karst areas. In the 1980s, karst collapse investigations were carried out in the Yangtze River basin, typical mines, well fields, and railway lines including the Guikun Railway. During this period, small scales of physical models were constructed to simulate the karst collapse processes. In the 1990s, karst collapse investigations were focused on six cities—Wuhan, Yulin, Tangshan, Tongling, Guilin, and Shenzhen. During this period, the Institute of Karst Geology in Guilin, China built a large physical simulation laboratory to simulate the sinkhole-forming process and to study the main factors contributing to the collapse occurrence in these cities. Such factors as mine drainage, pumping, rainfall, and the rises and falls of river level were investigated in the simulations. Since 2000s, the China Geological Survey has initiated a nationwide inventory of karst collapses. As of 2020, the karst collapse mapping on a scale of 1:5000 was completed over 30,000 km^2 of the typical karst collapse areas of south China (Lei and Dai 2018). Since the 2000s, the Natural Science Foundation of China has increased funding in karst collapse research and has launched 17 projects. Fifteen of these projects were on karst collapse mechanisms induced by pumping, pile foundation, shield, tunnel construction, mine drainage, train vibration, extreme climate, and natural conditions, whereas two projects were on the prediction and prevention of karst collapses.

The research on the mechanism of karst collapse began in the 1930s. Scholars from the former Soviet Union first proposed the theory of subsurface erosion, which is the phenomenon of soil particles moving under the action of seepage. Subsurface erosion includes both mechanical erosion and chemical dissolution. Since the early 1980s, researchers have made in-depth studies on the formation mechanism of karst collapses. Xu (1981) proposed the theory of vacuum suction through the experiences with karst collapses caused by dewatering in coal mines and ponding in reservoirs. Su (1982) put forward the theory of gas erosion and gas explosion. In the 1990s, Chen (1994) proposed the pressure difference as the driving force in karst collapse based on experience with the construction and operation of railways. Chinese scholars proposed other factors that may affect sinkhole formation such as gravity, blasting, vibration, unloading, and root erosion, depending on the site-specific conditions. In 1990s, American scholar Tharp (1999) put forward the hydrofracturing effect of karst collapse and the calculation method according to the hydrodynamic theory. The hydrofracturing of rock (soil) bodies is intensively studied in water conservancy dams. Studying the occurrence and expansion of cracks in the rock (soil) body revealed the mechanical response and structural changes of the rock (soil) body under the action of water pressure.

In-situ testing, triaxial apparatus, and centrifuges have been used to study hydrofracturing in soils. For example, two sets of in-situ hydrofracturing tests were conducted on the Teton Dam in the USA after the dam failure in 1976. The excavation of the test sections showed that almost all the test sections formed cracks and were vertical in the splitting surface, which was almost perpendicular to the dam axis. Hydrofracturing played a significant role in the dam failure process. The indoor tests were initially conducted using a model test tank. A triaxial apparatus was used to study the hydrofracturing damage mode, direction of splitting surface, and cracks propagation. Centrifuge tests were applied to studying the hydrofracturing performance of cohesive soils in the last decade. The hydrofracturing damage mechanism of soil includes shear failure and tension failure. The radial and tangential stresses around the perimeter of a hole lead to shear damage. The theory of tension damage is mainly because hydrofracturing occurs when the minimum effective stress becomes negative and exceeds the tensile strength of the soil. Some scholars also believe that hydrofracturing is a combination of the two mechanisms. Therefore, the tensile strength of soil is an essential mechanical parameter to control the hydrofracturing of soil. Wang et al. (2018) pointed out that there are original fractures in underground soil. Under the action of seepage water pressure, these fractures undergo expansion, and the final penetration process depends on the wedging action of water pressure. However, there is no sufficient evidence to prove the rationality. The Mohr–Coulomb strength theory applicable to the judgment of shear damage mechanism, although it was based on the elastic–plastic mechanics theory, is not readily applicable to explaining the crack expansion, while the judgment criterion of hydrofracturing corresponding to the tension damage mechanism is divided into the total stress criterion and effective stress criterion. All the tests above show that the initial cracking pressure of soil is related to the stress distribution of surrounding rock, shear strength of undrained soil, the ratio of center pore diameter to sample diameter, over consolidation ratio of soil, initial stress ratio, and compression speed.

The laboratory tests conducted by Liu et al. (2018) concluded that there was a positive correlation between the critical water pressure of hydrofracturing and the material strength and axial compressive stress. The axial compressive stress had a greater impact on the critical water pressure of hydrofracturing than the material strength. The critical water pressure of hydrofracturing has a negative correlation with the initial crack opening and initial crack length. With the increase of water pressure inside the seam, the fracture tip of the initial fracture of the rock mass expands, forming the damage degradation zone and macroscopic fractures. These processes lead to the instability and failure of the rock mass. The theoretical model can be divided into two categories. One assumes the rock mass as a fractured medium and considers that water exists and moves through the fractures of the rock body. The other assumes the rock body as an equivalent continuous medium and introduces the concept of damage to describe the development of fractures in rock mass in response to the change of rock stress. The water pressure is regarded as volume tension and establishes the relationship between the damage variable and the permeability coefficient. Damage mainly refers to the occurrence and expansion of fractures in the rock mass, which geometrically means the reduction of bearing area. Xie and Su (2004) pointed out the following assumptions in hydrofracturing study in a fractured rock mass with seepage-stress coupling:

- Rock near the fracture is impermeable or has no permeability.
- Water penetrates in a uniform medium, which is a hypothetical flow pattern.
- Water flow in fractured rock mass is a mixture of fractured flow and porous-medium seepage. When the fractures in rock mass are large, the conditions are more conducive to fracture flow or pipe flow.

Table 1.1 summarizes that the current karst collapse formation mechanisms are macroscopic hypotheses based on the geological conditions and influencing factors of the collapse. As the main driving force of the collapse, the effect of groundwater activity is manifested in two aspects: dissolution and transportation of water and sudden change of water pressure in karst conduits caused by water level change. Therefore, the research on the mechanism of karst collapse must analyze flow dynamics in the karst conduits. He and Xu (1993) believe that the real mechanism of collapse can be explored by studying the hydrodynamic conditions of flow and water–gas pressure characteristics in karst conduits. This is also the reason why the dominant karst collapse mechanisms involve subduction, vacuum negative pressure, pressure difference, and hydrofracturing. These processes are strongly associated with changing underground hydrodynamic conditions. In fact, the damage mechanism of changing groundwater dynamic conditions can all be attributed to the seepage deformation and failure of rock and soil, i.e., transport of soil particles or the whole soil/rock mass under the action of groundwater seepage force (hydrodynamic pressure) causes the deformation and damage of the formation. In the process of karst collapse formation, the action mode and direction of groundwater seepage on karst cavity roof rock/soil body can be different because of the change of groundwater dynamic conditions.

The mechanism of limit equilibrium theory of soil mechanics considers the problem of roof stability of karst cave, which is the last stage in the process of karst collapse development. The change of surface load only shortens the time of the collapse occurrence on the ground. Since the effect of groundwater is not considered, it is still open to discussion whether this process can be considered as the main mechanism of collapse.

The karst collapse mechanisms discussed above involve different disciplines such as hydraulics, soil mechanics, and seismology. These mechanisms are not only related to the change of hydrostatic pressure but also related to the effect of hydrodynamic pressure. Hydrodynamic pressure can be a new challenge and opportunity for the study of karst collapse mechanisms in the future.

1.2.3 Research Trend on Karst Collapses

With the application of fine optical fiber, accelerometer, sonar, and other measurement technologies, the monitoring frequency of the groundwater and gas pressure (or groundwater level) has increased from low frequency (such as 24 h) to high frequency (such as 5 min). The high-frequency monitoring is conducive to the determination of the macroscopic karst collapse discrimination index and the microscopic mechanism analysis of karst collapse under hydrodynamic pressure.

1.2.3.1 Study on Karst Collapse Criteria

Since the current research on karst collapse mechanism is still at the stage of qualitative macroscopic analysis, there is a long way to go to quantify these collapse-causing factors, such as the thresholds of hydraulic gradient, negative