

Management and mitigation of sinkholes on karst lands: an overview of practical applications

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Abstract When karst lands are developed for residential or commercial purposes, sinkholes are to be properly managed or mitigated. This paper discusses various types of sinkholes and their possible formation mechanisms, presents some guidelines for sinkhole management, and summarizes several engineering measures for sinkhole remediation. Because a sinkhole is often not an isolated feature but a component of an integrated groundwater and surface water system, knowledge of the sinkhole geology and hydrology is essential in selection of the proper management tools and remediation options. Adverse effects including flooding, additional sinkholes, and groundwater contamination can result from poorly managed or improperly repaired sinkholes.

Introduction

A sinkhole is a geologic feature that is characteristic of karst areas. Although its shape changes over time, it is usually thought of as a closed funnel-shaped or bowl-sloped depression. A depression can range from a few centimeters to several kilometers, however, the typical sinkhole size that is closely related to engineering activities ranges from tens to hundreds meters in diameter. A sinkhole is formed by erosion of soil and/or rock material into

the subsurface. Human-induced modifications on the karst lands can accelerate the erosion processes. The inexorable and continuous dissolution of soluble bedrock dictates that formation of sinkholes is a dynamic process. A sinkhole can be a natural drain to the subsurface, an entrance to a cave, or a collapse that destroys buildings and roadways. Surface water that funnels into a sinkhole seeps downward through the soil at its bottom or quickly drains into the subsurface if the sinkhole has an open swallet. Losing or sinking streams develop as sinkholes drain water from surface streams.

A sinkhole provides a convenient place to deposit trash. People who have sinkholes in their yards may want them to be filled in the hope that it will increase their property values or make their yards more usable. However, a sinkhole is not just a hole in the ground. It has geological and hydrological significance. Within the karst hydrologic system, a sinkhole usually develops as a drainage point into a subsurface conduit system. The conduits not only carry the recharge water from the sinkhole into the aquifer, but also transmit any suspended sediment carried by the turbulent flow and any materials resulting from human activities, including contaminants. A sinkhole may also be a part of an integrated ecological system that supports atypical species of plants or animals (Friend 2002). Disposal of materials into a sinkhole requires very careful geological and hydrological consideration. Any contaminants disposed of in sinkholes may end up in caves, springs and water wells in the area of the sinkhole (Zhou et al. 2005).

Commercial development of an area with sinkholes requires a comprehensive work plan to manage and remediate the sinkholes. A significant design aspect for deterring sinkhole development is to understand and control the surface and subsurface water. Too often, karst problems are tackled with various forms of engineering

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programs like grouting without careful consideration of their effects on the subsurface water flow. The advantages and disadvantages of grouting should be evaluated before it is implemented. Grout programs can provide a means to increase soil density for structure support. They can also seal an epikarst drain that directs shallow water into the underlying aquifer. However, the effect of sealing a subcutaneous drain may result in pooling and saturation of the peripheral area with a consequence of increased subsurface drainage to adjacent epikarst drains. In some karst areas, grouting of one sinkhole will only divert the underground flow elsewhere, resulting in the development of new sinkholes. Using grout to seal a natural drain also has the potential to restrict or occlude the underdraining conduit, which can lead to back flooding. Without an understanding of the processes that cause the sinkhole hazards, restricting the water flow into the existing sinkholes may change the flow dynamics in the local area.

Sinkholes and their formation

Karst areas are prone to sinkhole formation because of their intrinsic defects including irregular bedrock surfaces, voids in the underlying rock formation, and eroded and loosened soils with low penetration resistance. A sinkhole is a surface symptom of the complicated erosion processes that occur on the surface and in the subsurface. Figure 1 lists five commonly used engineering classifications of sinkholes. In modern literature, both doline and sinkhole are used to refer geomorphological features and are no longer distinguished by the mechanism of formation. Clearly, each classification system is based on the investigator's own experience dealing with the geotechnical and environmental problems

in certain geographic settings. Sinkholes can also be classified by their hydrogeological, geomorphological, or ecological properties. Although there is no consensus in sinkhole classification, most of the investigators agree on the processes that lead to sinkholes. A more comprehensive but genetic classification of sinkholes is recently proposed by Gutierrez et al. (2007) for the evaporite paleokarst in Spain. When defining the type of sinkholes in an area, the geologist or engineer should consistently follow one classification system. It may cause inconsistencies and confusions if more than one classification system is used. For practical purposes, the primary criterion is the type of surface material that moves downward. Sinkholes can occur in bedrock outcrops, caprocks, and in the overburden soils. The secondary criterion can be the mode at which the surface material moves. For example, sinkholes can be either a catastrophic collapse feature or a slow subsidence feature. It is important to note that the primary and secondary criteria focus on the processes on the surface. One should not confuse these surface processes with what may have happened in the subsurface to create the necessary conditions for a sinkhole to occur. Some sinkholes occur suddenly; however, the processes of creating the collapse may last years even centuries. On the other hand, some sinkholes appear to occur slowly as subsidence features; however, the processes of creating them may be considered to be geologically fast. Any further division of the sinkholes can be based on the exact causes that lead to the sinkholes. Williams (2003) takes a different approach to classify the sinkholes (dolines as preferred by Williams). The primary criterion used by Williams is the formation mechanisms for the enclosed depressions. He listed four main mechanisms: dissolution, collapse, suffusion, and regional subsidence. This classification may be theoretically logical

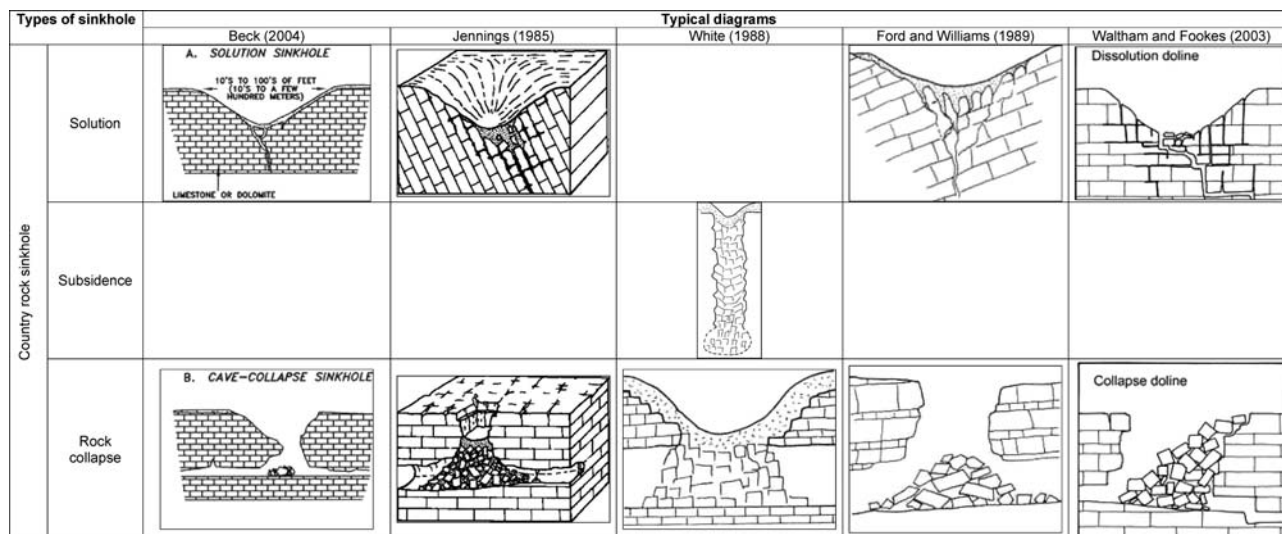


Fig. 1 Selected types of sinkhole (Beck 2004; Jennings 1985; White 1988; Ford and Williams 1989; Waltham and Fookes 2003)

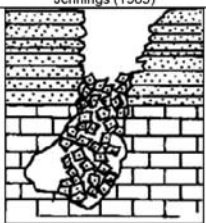
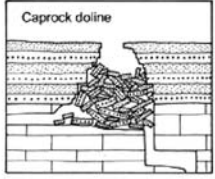
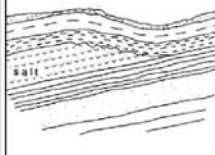
Types of sinkhole		Typical diagrams				
		Beck (2004)	Jennings (1985)	White (1988)	Ford and Williams (1989)	Waltham and Fookes (2003)
Caprock sinkhole	Caprock collapse					
	Caprock subsidence					

Fig. 1 continued

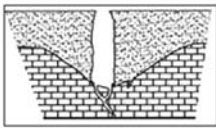
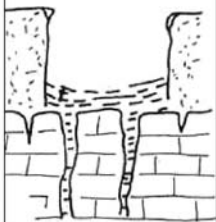
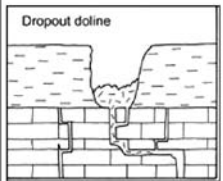
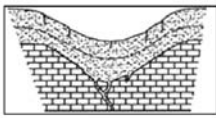
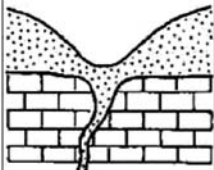
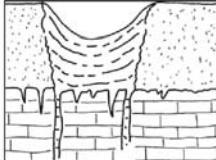

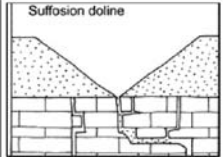
Types of sinkhole		Typical diagrams				
		Beck (2004)	Jennings (1985)	White (1988)	Ford and Williams (1989)	Waltham and Fookes (2003)
Overburden sinkhole	Cover collapse					
	Cover subsidence					
	Suffosion sinkhole					

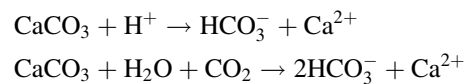
Fig. 1 continued

and scientifically sounding. However, practical application of this system faces challenges because many sinkholes result from multiple mechanisms. When a sinkhole is polygenetic in origin, it can be classified into more than one type. In addition, the exact mechanisms for a sinkhole are often not readily known. Many formation mechanisms are actually hypotheses, and convincing evidence to prove these hypotheses is difficult to collect in practice.

Sinkholes in soluble bedrocks

When a sinkhole occurs in the soluble bedrock, it is a bedrock sinkhole. Such type of sinkhole can have numerous shapes and sizes. Solution sinkholes and cave collapse

sinkholes are two types of bedrock sinkholes that are often encountered in bare karst areas. Solution sinkholes emphasize the chemical processes that dissolve the rock over time. A typical chemical reaction in limestone can be expressed by:



The bedrock dissolution continues as long as the water in contact with the rock remains aggressive. The dissolution process occurs on the surface, in the thin soil cover, or in the bedrock itself, where the water is mildly acidic. More rock is dissolved at locations where the water flow is more concentrated. Mixing of waters with different geochemical

properties tends to increase the power of dissolving carbonate rocks.

Collapse sinkholes focus on the mechanical breakdowns, although the chemical processes are important in developing the cave in the bedrock and removing the collapses materials. Caves develop when the dissolution process occurs within the bedrock. If the rocks above the cave are rigid, they collapse only when they cannot support the weight above the cave. Dissolution and mechanical breakdown are not mutually exclusive in sinkhole formation. The cave collapse sinkholes are the result of both, while the solution sinkholes may not necessarily involve mechanical failures.

Sinkholes in caprocks

Sinkholes can occur in non-soluble rocks when they are underlain by soluble ones. Under such geologic conditions, the overlying non-soluble rock such as sandstone is referred to as caprock, and the sinkhole formation processes occur in the subsurface. The contacts between the soluble and non-soluble rocks can be favorable locations to karst development. The caprocks can help preserve the karst voids as they are enlarged by dissolution. Mechanically, the formation processes of caprock sinkholes are similar to the impact of underground mining on the land surface. Depending on the mechanical properties of the caprock, the caprock sinkholes can be collapse features or broad bedrock subsidences as a result of gradual sagging. Factors such as paleokarstification in the underlying soluble rocks, interstratal karstification, vertical percolation of water, and fracture characteristics of the caprock control the formation of this type of sinkhole. Bedrocks above a void tend to be more fractured, which enhances vertical flow, while the enhanced flow can further enlarge the void. The void enlargement and enhancement of vertical flow are closely interrelated, and the processes are self-accelerating.

While the mining-induced subsidence occurs within a relatively short periods, the caprock sinkhole formation can be in a geological time frame. Solution-enlarged voids may exist in most carbonate rocks; however, not all caprocks develop sinkholes. In addition to the typical carbonate acid solution, other geologic processes may be also involved in the caprock sinkhole formation. One of the processes may involve gypsum dissolution, which can significantly accelerate the dissolution processes. The basic chemical reaction of gypsum dissolution is expressed by:

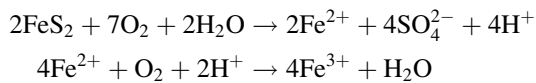


In areas where thin layers of gypsum are interbedded with limestone or dolomite, the potential for the hydration of anhydrite and the dissolution of the resultant gypsum is

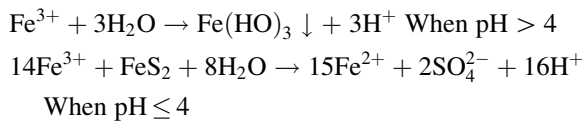
large. When anhydrite hydrates to gypsum, the expansion can cause brecciation of the mineral, brecciation of adjacent rock, and injection of fibrous gypsum veins. When dissolution of the gypsum occurs, cavities result followed by collapse and formation of layered breccia deposits. When gypsum is in contact with carbonate rocks, the water chemistry associated with the dissolution is different from that for limestone alone. Waters rich in calcium carbonate can aggressively dissolve gypsum and simultaneously deposit calcite. When this occurs, the breccia caused by the dissolution of the gypsum may be cemented. Gypsum dissolves easily in flowing water and increases the amount of sulphate in the water. The solubility of gypsum in calcium carbonate-rich waters may be decreased by the common ion effect. Conversely, the presence of sodium, magnesium and chloride ions can enhance the dissolution of gypsum. Experimental works by Lu (1996) shows that the presence of sulphate in water increases the dissolution rate for dolomite. For water with an SO_4^{2-} content of 1 mg/l, the dissolution amount for dolomite was 1.67 mg/l, while the dissolution for limestone was only 0.94 mg/l. The result of this groundwater chemistry on karstification is that very intense and pervasive leaching of the carbonate deposits, especially, dolomites, can occur resulting in a honeycomb structure of very little strength. This dissolution process facilitates the development of collapse columns or breccia pipes that may propagate upwards through several strata.

In China, coal mining has exposed approximately 3,000 caprock collapses in 45 mining areas. The greatest concentration of caprock collapses is in Xishan Mine, Shanxi Province, where 1,300 such collapses are recorded in 18 km². These collapses have diameters from several tens of meters to several hundreds meters. They penetrate through the overlying Carboniferous and Permian coal sequences. Some caprock collapses contain sedimentary rocks as young as Triassic age, even though these young rocks have now been eroded away from the local area. These caprock collapses can be as high as 300–500 m. The majority of the exposed caprock sinkholes in the coal mines are within the zones where paleo-dissolution features are obvious. These paleo-features functioned as preferential flow paths in the geologic past, and they can still be hydrologically active in groundwater flow and contaminant transport (Zhou and Li 2001).

The fact that the caprock collapses in the coal mines are common along paleo- geological structures suggests that the oxidization of pyrite may be another source of acid in dissolution of the limestone. Pyrite occurs in the coal strata. The chemistry of pyrite weathering has been extensively investigated because of its direct relation with the acid mine drainage. Oxidization of pyrite provides sulfuric acid that reacts with the limestone to produce gypsum.



Then



The continuous solution of gypsum is enhanced by the continuous movement of groundwater.

Sinkholes in overburden

When a karst area is mantled by unconsolidated materials, the sinkhole formation processes become more complicated because of the involvement of soil erosion. In general, there are two types of sinkhole that occur in the overburden, cover-collapse sinkhole and cover-subsidence sinkhole. Such a classification emphasizes the rate at which the surface subsides, although the subsidence rate is evaluated in a descriptive term. Cover collapse sinkholes often occur suddenly, and their damages to properties are noticeably quick. Cover subsidence sinkholes are not readily perceptible, and their damages are more accumulative.

Formation of a cover collapse or subsidence sinkhole is probably preceded by formation of soil void at the soil/rock contact by transporting of soil into an opening in the bedrock. It is common that exploratory boreholes encounter a zone of soft soil just above the bedrock. The soft soil may be protected from compaction by rock pinnacles or overhangs. The soft zone may be indicative of an on-going sloughing process of the soil. The strength of this soft soil is very weak, and it can be easily transported into the opening in the bedrock. If the strength of overlying soil is strong enough, the roof of the soil void tends to approach a no-tension cylindrical or domal shape. If this condition has been reached, the load is carried in compression. Stress-strain analysis indicates the collapse or stability of the residual soil void is controlled by the relationship between the diameter of the void and the thickness of overburden when the cohesion remains constant (Yang and Drumm 1999). For soils with cohesion of 25 KPa, the void tends to enlarge when the overburden thickness is less than 2.5 times of the diameter of the void. Such relationships were also illustrated by experiments of physical models for weakly cemented sand (Gooding and Abdulla 1999). For cemented sand with cohesion of 43 KPa, the void could progress to the surface if the thickness of sand is less than one fourth of the void diameter. The physical experiments indicate that the weakly cemented sand behaves similarly to badly fractured rock, in which a tunnel roof could

remains stable when its thickness exceeds approximately one-fourth of the tunnel width (Peck et al. 1974). Clearly, such analyses emphasize the self-weight of the overburden as a driving force to enlarge the void. Practical investigations, however, have suggested that sinkholes occur above relatively small soil voids. Cavities of 0.2 m in diameter can cause sinkhole collapse in over 15 m thick overburden. Tank experiments, as discussed in Zhou (1997) demonstrated that collapse could reach the surface regardless of the thickness of the soil, as long as the fracture system was not blocked by the collapsed soil. The collapse process ceased every time when the fracture was filled with the soil; and restarted after the filled soil was removed. The reason for such a discrepancy is that the stress-strain models ignored the effect of water activities on the sinkhole formation.

It is our experience that water activities are the most important factor in development of cover-collapse or cover-subsidence sinkholes and in developing solution and cave-collapse sinkholes. Water is an enabling mechanism. As water seeps downward through the soil overburden or as the water level fluctuates in the formations, soil is eroded into solution-enlarged cracks in the underlying bedrock. Temporary formation of a dome-shaped void often concentrates seepage in that direction, thereby accelerating the erosion/raveling process. Continuing downward seepage enlarges the void upward toward the seepage source, shortening the seepage path and enlarging the “catchment area” of the void. Under this mechanism, the rock cracks or channels need not be large. An opening as small as a few centimeters may be the exit for an erosion-raveling dome several meters high if the water and the suspended solids can be transported into the network of solution-enlarged conduits.

Dome formation and enlargement in overburden soil occur naturally. The processes can be accelerated by changes in water flow conditions. A rise in the groundwater level from below the soil-rock interface to above the interface will increase the degree of saturation of the soil, decreasing the soil strength. An erosion process may not start because the water helps support the soil. A subsequent drop of that elevated groundwater level is accompanied by the loss of the buoyancy support, which may initiate the acceleration of raveling processes. Presence of a large void may not be a necessary prerequisite for a cover collapse sinkhole if a rapid water level drawdown is anticipated.

The impact of water on sinkhole formation was analyzed by Anikeev (1999) and Sharp (1997, 2003) based on hydrofracturing theory. Anikeev (1999) proposed a simple hydrofracturing criterion that is controlled by the ratio of soil cohesion to the loss of buoyant. A 3 m of drawdown in water level could cause hydrofracturing in soil with cohesion of 25 KPa. While Sharp's numerical analyses indicate that hydrofracturing was unlikely to occur under steady

state pore pressure. Transient pore pressure is a more probable cause of failure. The increased load accompanied with the loss of buoyancy support caused by a rapid drawdown of water table is initially shifted to the pore water. The effect occurs at the perimeter of the soil void, where it is manifested in high pore pressures and consequently high pore pressure gradients. If the gradient is greater than the stress gradient, hydrofracturing will occur and the void will be enlarged. The new free face that results will exhibit the same high gradient. This will result in a progressive failure that may proceed rapidly, accounting for the locally sudden appearance of sinkholes. The critical factor in this example is the rapidity of drawdown. If drawdown were slow enough to allow consolidation without a significant pore pressure transient, sinkhole formation may be slowed down.

In general, there are five ways that water flow may increase the pore pressure gradient around a soil void or/and decrease the cohesion in the soil:

- Surface water percolating downward: Water sources include parking lots, roadways, roof down-sprouts, catch/detention basins, irrigation lands, construction sites, and runoff from impervious surfaces and reservoirs.
- Near-surface water percolating downward: Water sources in this category include leakages of water lines, stormwater drainage system, sewer lines, or irrigation systems and natural water flow within epikarst zones.
- Groundwater level fluctuations: Water sources include mine dewatering, water inrush from quarries and mines, pumping at supply wells, long durations of dry and wet weathers. Extensive dewatering in a thick limestone aquifer may result in two or more temporary aquifers that have different water levels but are hydraulically connected.
- Water percolation from a shallow aquifer to a deeper aquifer: This often occurs in a dual aquifer system where the water level in the shallow aquifer is higher than the potentiometric pressure in the deeper aquifer. It can also occur in a thick aquifer system where perched water is present in the upper section.
- Water uprising from a deep confined aquifer to a shallow aquifer or to surface. This occurs when a confined aquifer is hydrologically connected to a shallow aquifer or to a surface water body.

Sinkhole management plan

It is generally acceptable not to construct any facilities within a sinkhole because of concerns of flooding, future collapses, and potential impact on groundwater. However,

whether a safety zone around an existing sinkhole can be defined depends on the site-specific conditions and the type of facility to be constructed. In areas where sinkhole data is available, geostatistical methods may be used to determine the radius of influence of a sinkhole. The spatial distribution of the sinkholes in a particular area is often clustered. New sinkholes tend to develop in the vicinity of the old ones because the hydrogeologic and topographic settings for the old sinkholes are favorable to sinkhole development, and the existing sinkholes may further enhance the solution and erosional processes. Stochastic analysis of the sinkhole distribution along Interstate 70 near Frederick, Maryland, indicated that the radius of influence of a sinkhole was approximately 30 m (Zhou et al. 2003). At another study site in Missouri, the radius of influence of a sinkhole was estimated to be approximately 244 m (Zhou et al. 2005). These quantitative analyses may provide technical background for determination of the necessary setbacks from sinkholes.

Very often, the sinkhole data is not available for an area or the data are not systematically analyzed. Under such circumstances, the setbacks can be determined by discussions among different groups including developers, regulators, and concerned citizens.

For residential and commercial buildings, relatively small setbacks are often used. In Monroe County of Indiana, the setback is 7.6 m (25") for sinkholes no more than 0.1 ha. For sinkholes larger than 0.1 ha the setback should be 15 m of the post-development sinkhole flooding area or 7.6 m from the rim of the sinkhole, whichever is less. In Knox County and the town of Farragut of Tennessee, a 15 m setback is recommended around an existing sinkhole. Any construction within 15 m radius should not compromise the drainage function of the sinkhole and should not cause any adverse impact on groundwater, and the developer should obtain all permits from the Tennessee Department of Environment and Conservation and provide evidence that there is no more danger from building in this area than there would be in other areas.

Construction of liquid manure storage requires relatively larger setbacks. In Minnesota, for example, any liquid manure should not be constructed 91 m from the outside edge of a sinkhole (Minnesota Pollution Control Agency 2000). Kentucky, Missouri, Wisconsin, and Iowa have setbacks from sinkholes of 46, 91, 122, and 152 m, respectively (*ibid*). Many states also rely on the engineering designs to ensure the safety of the facilities.

Construction of landfills around sinkholes is more complicated. The U.S. EPA and several states including Kentucky, Indiana, Maryland, Pennsylvania, Georgia, and West Virginia have specific requirements for such facilities (Davis 1997). Whether the area adjacent to a sinkhole is suitable for landfill sitting or how far away the facility

should be constructed from the sinkhole depends on the degree to which the karst develops. Travis et al. (2000) and Hatheway (1996) provided detailed discussions on this topic.

Little runoff is present on well-developed karst lands. Overland flow during storms disappears into sinkholes to enter the groundwater system as internal runoff. In many engineering designs, surface runoff and the associated contaminants are disposed of into the existing sinkholes. Runoff from roadways, parking lots, and other impervious areas frequently discharges into sinkholes carrying highly turbid water, road salt and hydrocarbon contaminants from automobiles.

A sinkhole that has been modified or altered to promote or accept stormwater drainage is considered to be a Class-V Injection Well. Class-V Wells are regulated under the authority of the Safe Drinking Water Act, U.S. EPA Underground Injection Control Regulations, and the relevant state rules. When a sinkhole is permitted and managed as a Class-V Well, it should present any injection activity from endangering underground sources of drinking water.

Sinkhole terrains, especially in regions of shallow water table, are flood-prone. Sinkhole flooding can be caused by surface runoff and groundwater flow. When the soil within a sinkhole is less permeable, a temporary pond or lake may be perched above the local groundwater table after rains. Sinkhole ponds may take days or weeks to drain. On the other hand, when sinkholes lack of impermeable soil, they connect the underlying groundwater system through their drains and they are part of the aquifer system. Rising of groundwater levels forces water back up through the drain to pond in the sinkhole. The sinkhole functions as a large-diameter monitoring well. The standing water level in the sinkhole is the surface expression of the groundwater table, and such a sinkhole can be considered as a karst window. A spring forms when water spills out of a sinkhole. Grouting when it is used to remediate sinkholes or sinkhole-prone areas can also cause sinkhole flooding. Grouting may inadvertently seal off the subsurface drains and dam the groundwater flow. Special zoning restriction or other stormwater runoff control measures may be required to control the flooding problem.

In rural areas, sinkholes represent lost acreage from farming. In urban areas, sinkholes may be efficient drains for sewage or contaminated storm water runoff from streets and parking lots. Because sinkholes are the loci of water recharge to the karst aquifer, waste placed in them or the leachate can be carried directly into the groundwater. Once emplaced underground, these materials acts as source of pollution which can continue to function for long periods of time, even long after remedial measures have been taken on the sinkhole itself.

Selected best management practices over sinkholes include:

- On-site personnel should be thoroughly briefed on the special protective measures recommended for sinkholes and the safety concerns associated with operating within and around them.
- If previously unidentified sinkhole is encountered during construction, operating activities should cease until the feature is properly assessed.
- Avoid excavation activities during storm events or periods of sustained heavy rainfall to reduce the potential for soil erosion and sediment transport into the subsurface.
- Maintain natural surface drainage pattern as much as possible to avoid disrupting natural subsurface flow.
- Pile any surplus surface materials away from sinkholes.
- Minimize clearing of vegetation within sinkholes as much as possible to provide suitable areas for infiltration of surface runoff.
- If blasting is necessary, controlled blasting techniques should be used to minimize the vibration and sound waves.
- Avoid fuelling or servicing machinery near sinkholes.
- In areas where sinkhole is a common occurrence, conduct geophysical investigation to understand the subsurface conditions and identify any buried sinkholes.
- Document all information regarding the sinkhole including dimensions, shape, drainage area, swallet information, and type.
- Design erosion and sediment control and stormwater management facilities so that the excavated materials do not drain into sinkholes.
- Depending on the size of the tributary drainage area, the runoff water quality, and the difficulty of establishing an alternate outlet, sinkholes may need to continue accepting some or as much water as in the past. A filtering system design may be necessary to prevent lateral erosion while allowing water to pass. A Class-V Injection Well permit is required for this operation.
- If the sinkhole may undermine the safety of the construction site, the sinkhole should be remediated appropriately or engineering measures should be taken to assure that the facility remains undamaged.
- Keep the wheels or tracks of ground-based machinery away from the edge of the sinkhole for safety of the operators.
- Whenever uncertainties arise, always work with a qualified geologist to develop specific best management plans for each sinkhole.

In general, stormwater runoff management constitutes the most important part of sinkhole management plans on karst

lands. In a sinking stream where a portion or all of the stream flow recharges into the underlying karst aquifer through a sinkhole, the sinkhole management will include the surface watershed upstream of the sinking point. Such a

sinkhole is not listed in Fig. 1 but is often referred to as alluvial streamsink doline (Jennings 1985), swallet, or ponor. The management of such a sinkhole should be included in the watershed management plan of the surface

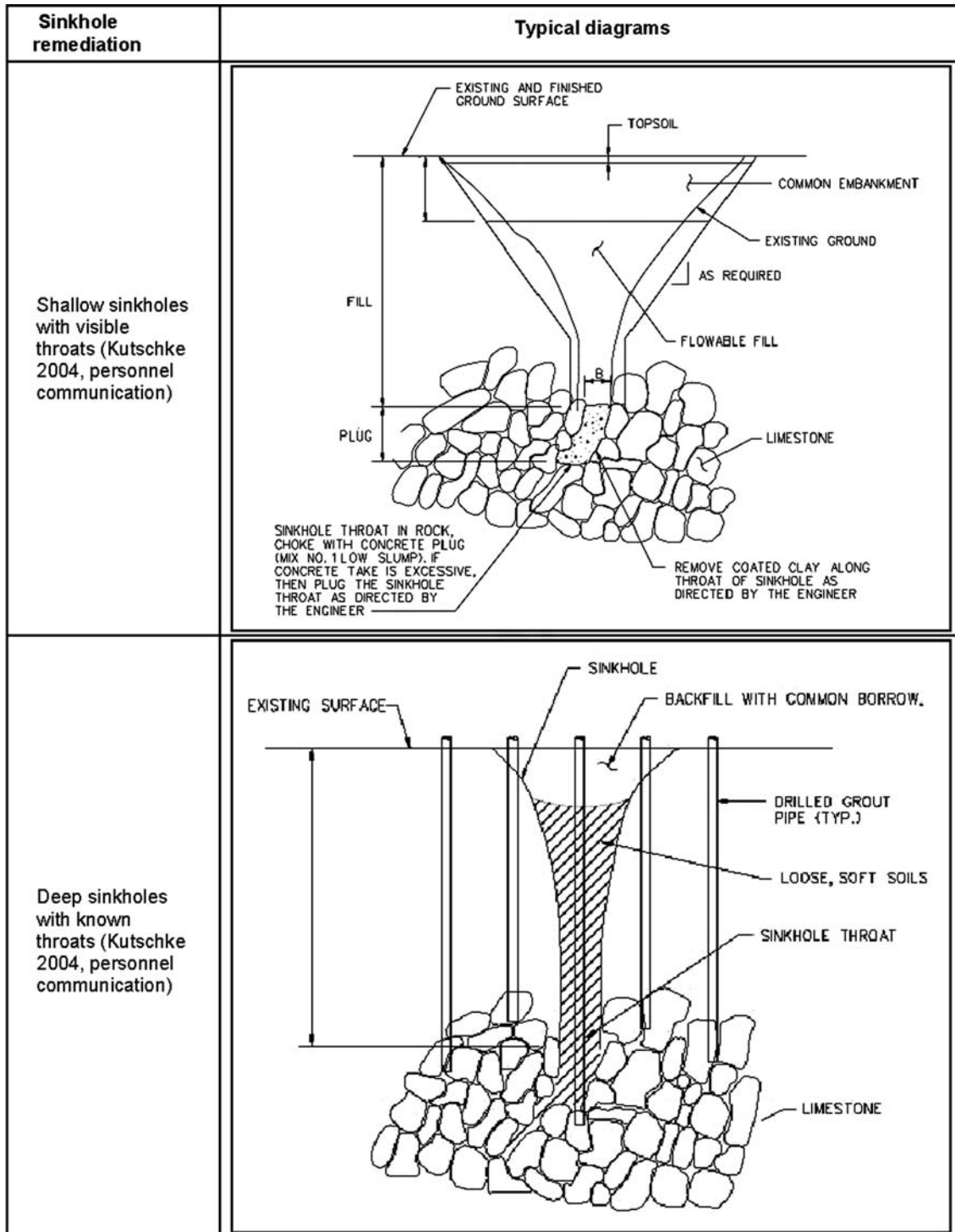


Fig. 2 Selected options for sinkhole remediation (Kutschke 2004, personnel communication; Siegel et al. 1999; Fort Campbell Environmental Division 2003; Beck and Zhou 2002)

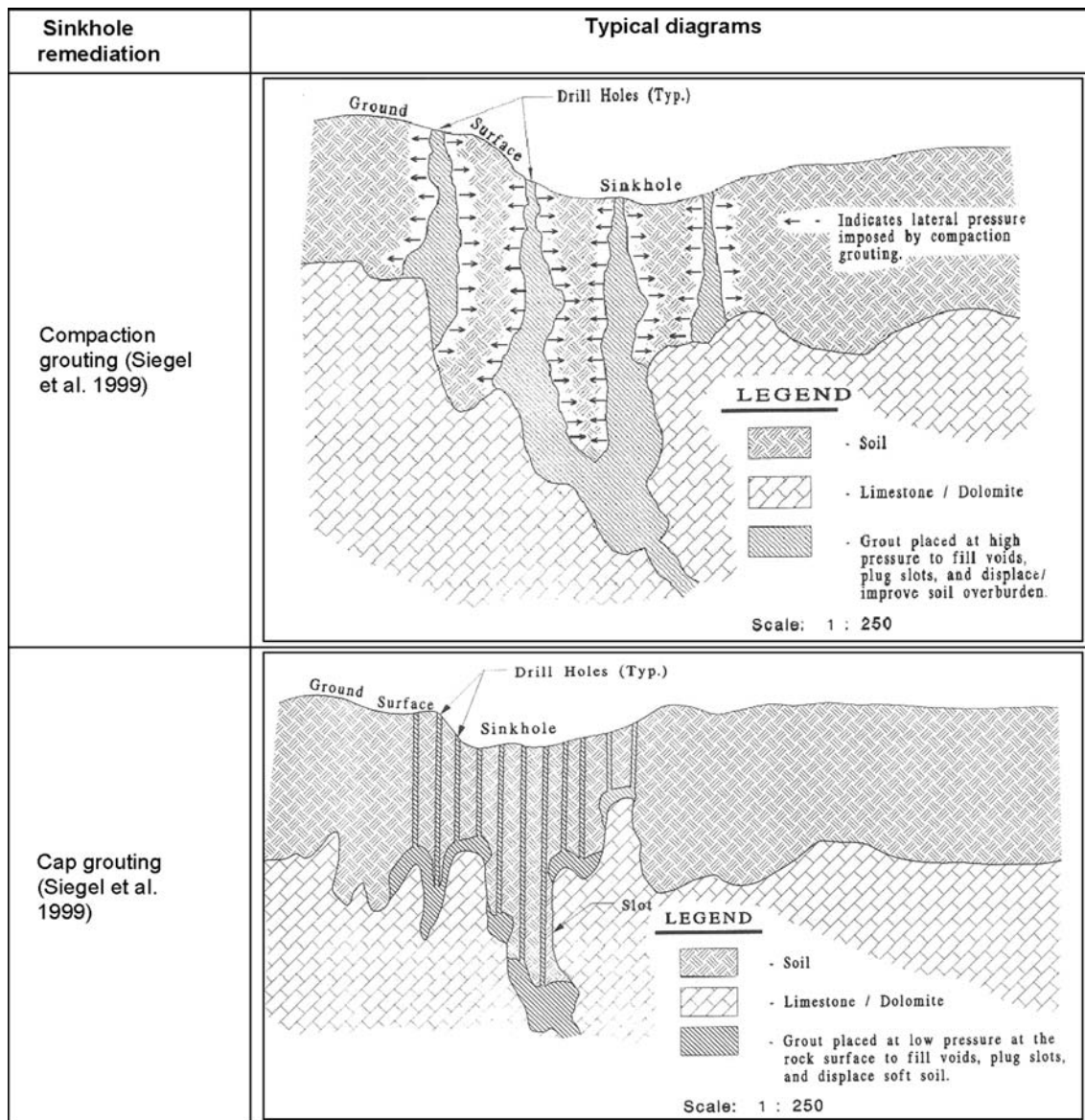


Fig. 2 continued

stream (EPA 2005). The surface watershed management should emphasize the potential impacts of land development on both the surface water and groundwater systems.

Sinkhole treatment options

Sinkhole mitigation is to repair the existing sinkholes and to prevent their reactivation in the future. To successfully remediate a sinkhole, a thorough geotechnical study should be performed by knowledgeable professionals such as geotechnical engineers and geologists to understand how it is formed. The characteristics of the sinkhole and the intended use of the sinkhole site determine the mitigation

approach. For sinkholes that are related to water activities, the most intuitive and straightforward means of preventing sinkholes from occurring is to eliminate the various water sources. Elimination of the water sources eliminates the erosion processes that lead to sinkhole formation. When it is difficult to eliminate the water sources, the second choice is to work on the passageways through which the water moves. The third option is to reinforce the strength of soils/rocks. The overall purpose of the engineering measures is to either eliminate or significantly reduce the erosion processes. Success in sinkhole mitigation relies on the extent to which the erosion processes are eliminated. Sinkhole treatment should consider the unique characteristics of each individual sinkhole. The engineering measures for

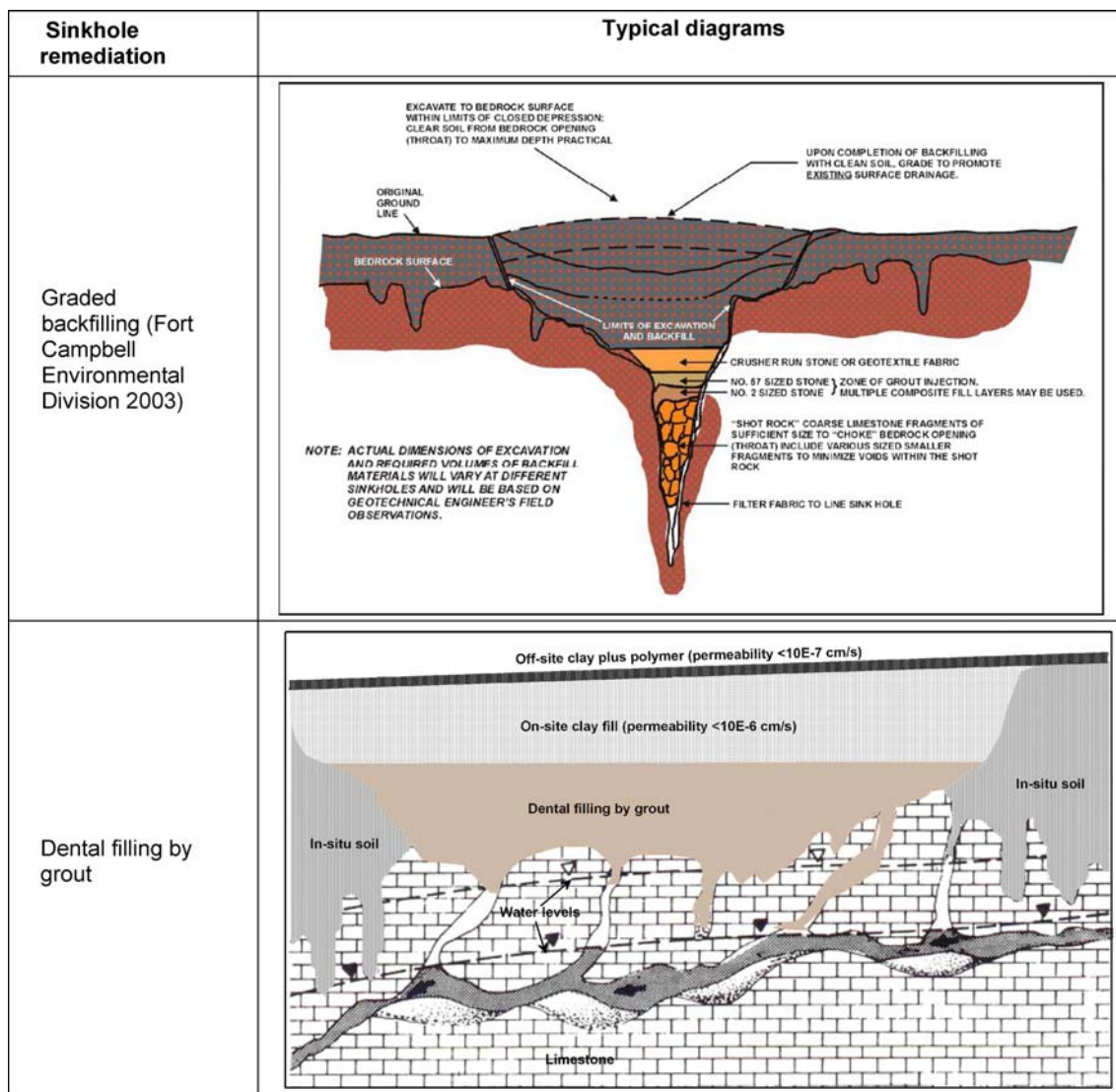


Fig. 2 continued

sinkhole mitigation should be tailored to each sinkhole. Sinkholes that are in a springhead or wellhead protection area should be treated differently from those outside the protection area. Figure 2 lists eight commonly used remediation methods. These methods provide only the basic principles of sinkhole remediation. They are not engineering designs. Any engineering measures need to be tailored to reflect the unique characteristics of the sinkhole to be treated and its geologic and hydrologic conditions. A direct copy of any of the selected approaches is not recommended. Although there is no option that fits all sinkholes, it is our experience that successful sinkhole mitigation should include treatment of sinkhole throat, fill of sinkhole body, and construction of sinkhole cap. In some areas, sinkhole remediation may be regulated, and any

engineering measures should be reviewed by regulatory agencies and local engineering offices.

Treatments of sinkhole throat

There are many ways to treat sinkhole throats. Because the configuration of each sinkhole is unique, knowledgeable professionals are needed to determine the most appropriate approaches. In general, selection of treatment methods depends on the complexity and uncertainty about the sinkhole and its depth. For mitigation purpose, sinkholes can be divided into shallow sinkholes and deep sinkholes. Shallow sinkholes are those that are no more than 10 m deep, and their bottoms are reachable by a regular backhoe.

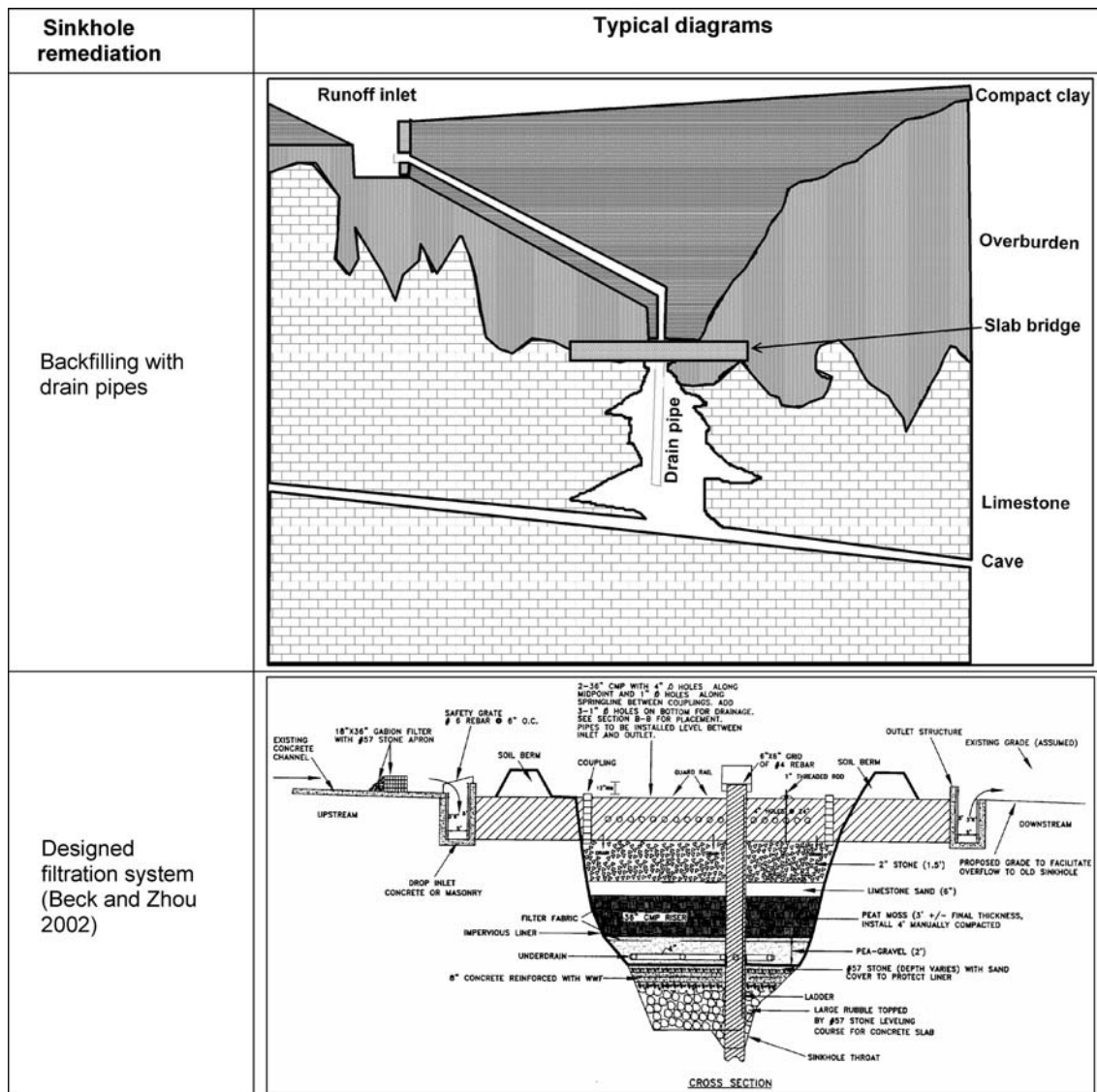


Fig. 2 continued

Deep sinkholes are more than 10 m deep, and drilling rigs are needed to reach their bottoms.

Shallow sinkholes (≤ 10 m)

Excavating and throat plugging

This is the most intuitive and simplest solution to remediation of an existing sinkhole. In many cases, it is cost-effective and may work for a long time. It is relatively a quick solution for constructions that can tolerate minor subsidence, and reactivation of the sinkhole will not cause significant property damage and will not threaten people’s

life. Selection of this option assumes that a sinkhole throat exists and the throat can be exposed by excavation. The excavation process should make sure that the sinkhole throat is free of clayey materials. One rock piece or a layer of large stones can be used to plug the drain. The pluggers should be compacted to ensure that they are jammed in the throat and are structurally stable. The plugging materials can also be made of concrete blocks. A grout plug is probably the most effective approach to remediate a sinkhole (Sowers 1996). The objective is to plug the sinkhole throat with concrete to an approximate depth of 1.5 times the width of the throat. To the extent possible, any clay coating along the throat should be removed before concrete placement to secure a good bond between the concrete and rock.

Excavating and fracture filling

Not every sinkhole has a throat. If the sinkhole does not have an obvious throat, but consists of many discrete fractures, these fractures can be impermealized by dental infilling grout. Pressure wash is recommended to help identify the fractures at exposed bedrock surface at the sinkhole bottom. Grout pockets are scraped at the fracture zones. If necessary, pressure wash should be applied to ensure that the grout pockets are free of clay. The pockets are filled with high/low slump flowable fill to plug and cap the fractures.

Deep sinkholes (≥ 10 m)

For deep sinkholes, their bottoms cannot be exposed for visual inspection. The characteristics of sinkhole bottoms can only be interpreted through borehole exploration or/and geophysical surveys.

Compaction grouting

Compaction grouting is often used to plug the throat of a deep sinkhole. Grouting holes are drilled into the sinkhole and its vicinity. Relatively high grout pressure of 1,380 kPa or greater is used in the grouting holes to fill voids, plug fissures around each hole, and displace/improve the soil/rock within a sinkhole. Primary grouting hole spacing is typically 3.5–5 m. Higher grout pressure, greater grout hole spacing, higher grout quantity refusal criteria, and overburden treatment generally resulted in a larger grout intake. Compaction grouting is typically performed at the soil overburden or/and shallow rock within sinkholes. This technique may not work well in wet silts and clays.

Although drilling tools usually allow penetration through boulders and rock lenses, the large primary grout hole spacing may make it possible to miss the sinkhole throat or other major karst features. Secondary holes may be required. In between permeability tests are recommended to determine the effectiveness of grouting.

Compaction grouting may cause additional fractures due to hydrofracturing if it is not designed properly. Because of the wide spacing, this technique may be less effective in pinnacled rock. Potential sinkhole features may be located between the grout holes and grout may not be delivered to the sinkhole features. Another concern of compact grouting is that compact grouting can inadvertently seal off conduits that may be groundwater passageways.

When the infilling of a sinkhole throat is too stiff to displace with high pressure, a more effective technique, jet

grouting, may be successful. This process involves pumping a fluid grout into the soil with a rotating high-pressure jet. The jet erodes soil and cuts stiff clays and soft erodible rock into gravel to small boulder-sized pieces. Pressures of 30–50 MPa are typical at the grout nozzle. The pressure dissipates rapidly within the soil and does not cause heave when the volume of the grout is properly controlled. The larger particles of soil, including sand and gravel in the sinkhole filling, mix with the grout, producing a mixed-in-place concrete.

Cap grouting

Cap grouting is often a viable choice when a sinkhole is associated with small but discrete fractures at the bedrock surface and the area to be treated is extensive. Cap grouting uses low grout pressures, 140 kPa or less to pump lean cement at the bedrock surface to cover the sinkhole bottom to fill voids, plug fissures, and displace soft soil. This operation provides support to the upper layer and disconnects any vertical hydrologic connections. Improvement of overburden soil is not obvious. Grout hole spacing is typically 0.9 m. In general, cap grouting does not consume as much grout as compaction grouting. On the other hand, a good coverage to intersect sinkhole features requires closer grout hole spacing, which in turn requires greater drilling footage. Auger drilling may not extend to bedrock due to shallow refusal on floaters. Although the hydro-fracturing possibility is limited for such an operation, the ground surface elevation is observed for heave.

Other options

Because of the uncertainties in sinkhole characterization, other options should also be considered. For bottomless sinkholes in which bedrock is not reachable within a reasonable depth by boring, sinkhole mitigation occurs within unconsolidated soil or materials collapsed into the sinkhole. Several approaches including jet grouting, vibro-compaction or dynamic compaction may be applicable.

Dynamic compaction is a system generally used to densify granular soils to depths of approximately 3–12 m. The technique involves dropping heavy weights, 5–30 short tons, on the soils from a pre-determine depth. Vibro-compaction uses larger diameter depth vibrators to densify and strengthen granular soils or to create stone columns in mixed or layered fine grained soils. Jetting grout can be used when the infilling of a sinkhole bottom is too stiff to displace with high pressure. This process involves pumping a fluid grout into the soil with a rotating high-pressure jet. This jet erodes soil and cuts stiff clays and soft erodible

rock into gravel to small boulder-sized pieces. Pressures of 30–50 MPa are typical at the grout nozzle. The soil particles mix with the grout, producing a mixed-in-place concrete.

Slurry grouting can be another option. This method involves the injection of various mixtures of very fluid grouts into the ground. It fills cavities at virtually any depth that can be drilled. It can run along the plane of weakness of the limestone and overburden forming very effective seals. Because little to no densification of overburden soil takes place, the potential remains for building settlement problems.

Filling of sinkhole bodies

Up on the appropriate treatment of the sinkhole bottom, the sinkhole itself can be backfilled with selected materials compatible with future loadings. If a sinkhole remediation area is outside the footprint of a structure, settlement of the backfill material may not be a significant concern. Therefore, the backfill material could consist of common borrow tamped in place. If a sinkhole remediation area is within the footprint of a structure, settlement of the backfill material is of a concern. The backfill material should consist of relatively non-compressible material. Therefore, the backfill materials and placement procedures should be compatible with the anticipated loading and tolerable settlement. It is also essential that the filling materials should be analyzed for chemical compositions to ensure that they are not contaminated. Prior to filling, it is a common practice to line the sinkhole bottom and walls with a geotextile filter fabric. To prevent the sinkhole from reactivating, the following three filling methods are recommended. If a sinkhole is expected to continue as a drainage point, some drainage structures may have to be constructed to facilitate this purpose. If the water is contaminated, a filtration system may be necessary to treat the runoff prior to directing into the sinkhole.

Filling with compacted clay

The fill practice is to create an impermeable body to stop both vertical and lateral water flow. The fill consists of compacted clay with permeability less than 10^{-6} cm/s. Thin layers of soil are recommended as the compaction pressure transmitted to the soil decreases with soil depth. A high degree of compaction breaks down most aggregated or flocculated clay particles and makes them less permeable. Compaction helps to break up the vertical structure of the soil and greatly slow leakage.

Filling with graded filter

Inverse aggregate graded filter consists of placing rocks/boulders wider than about half the throat opening width into the solution enlarged fracture/joint to arch across the bottom opening. Successive layers are sized finer than the underlying layer but coarse enough not to pass through the interstitial spaces of the bed beneath. It can be permeable from top to bottom. In most cases, this kind of filters is permeable at lower section and impermeable at the upper part. This design allows subsurface water moving at the soil/bedrock interface to access the epikarst drain and groundwater recharge to occur but stops the surface percolation. Geotextile filter fabrics and even cement–grout mixes may be used when the stone layers are emplaced. Vibration shall be used to consolidate the seal and promote the infiltration of the grout into stone pores. The grouted zone should not penetrate below the groundwater level.

Filling with designed filter

Development of filtration techniques may help reduce the concentration of the contaminants in the runoff prior to flowing into a sinkhole. Keith et al. (1995) discuss the installation and contaminant removal efficiency of rock and peat filters constructed within sinkholes. Preliminary findings indicate that one peat filter removed approximately 80% of suspended particulate materials [measured as total suspended solids (TSS) and selected total recoverable metals] and about 50% of the dissolved copper and zinc. Rock filters removed approximately 33–76% of the TSS and 35–55% of the total recoverable metals. The field tests of an aboveground peat filtration system in eastern Knoxville, Tennessee indicate that the system can decrease the concentrations of polyaromatic hydrocarbons by 95% and total lead by 70%. The system was not efficient in removing the total petroleum hydrocarbons, zinc, and the total dissolved solids. The removal efficiency varies with the concentration of the contaminants in the runoff (Beck and Zhou 2002).

This remediation technique considers not only the stability for the site but also the water drainage. This kind of filters is permeable to surface water percolation but stops any lateral flows into the sinkhole. This technique is viable when the sinkhole is an indispensable drainage point. It requires an engineering design of a filtration system based on the sinkhole configuration and the amount of runoff flowing into the sinkhole. The filter materials need to be selected according to the water quality of the runoff so that the contaminants can be removed prior to recharging into the aquifer. The filtration system is also designed to support the stability of the sinkhole site. When sinkholes are

improved for drainage purpose, they are considered to be Class-V injection wells. Therefore, this option needs to be evaluated according to the relevant state laws.

Construction of sinkhole caps

The filled sinkhole needs to be capped by a clay layer about 0.2–0.5 m below the planed surface to further prevent water percolation. Use the native soil to bring surface grade to at least 0.15 m above the surrounding ground surface to ensure a positive drainage. Seed and mulch the completed area to reduce soil erosion.

The purpose of surface or near-surface grading is to further reduce the probability of water infiltration. One commonly used method is clay compaction. A high degree of compaction breaks down most aggregated or flocculated clay particles and makes them less permeable. Compaction helps to break up the vertical structure of the soil and greatly slow leakage. Thin layers of soil, each about 0.15 m thick, are recommended as the compaction pressure transmitted to the soil decreases with soil depth. When clay compaction is used in areas where cycles of drying and wetting or freezing and thawing occur, one needs address the possibility of reaggregation of the particles.

Permeability of coarse-grained soils (sands and gravels) can be greatly reduced by mixing the soils with bentonite. Bentonite is clay with a high shrink–swell ratio. It can be mixed with existing soils and compacted in layers. Upon wetting, the bentonite will swell to many times its dry volume. This action tends to seal soils that lack clay-size particles. Bentonite is most effective on soils that contain less than 50% fines and with plasticity indices less than 15. Only sodium bentonite should be used for pond or reservoir sealing.

To seal sinkholes where water ponds it may be necessary to add a chemical dispersant. As with bentonite, these chemicals should be thoroughly incorporated into the soil. Soda ash, Sodium chloride, and Sodium polyphosphate are chemical dispersants. They change the soil structure by replacing a bivalent calcium ion with a mono-valent sodium ion. Chemical additives work only when the clay particles are present in clusters. For best results with chemical sealing, the soil should be fine grained with at least 15% finer than clay size (0.002 mm). Soluble salts should be less than 0.5% of dry soil weight. Dispersants should be mixed in 0.15 m lifts of soil and compacted. The amount of compaction will affect the permeability rate. The minimum thickness of the finished treated blanket should be 0.15 m for water depths of 2.5 m or less and proportionally thicker for greater water depths. ESS-13 is another soil sealant, which is a vegetable oil based liquid polymer emulsion (<http://www.ess13.com>). Because the ESS-13 molecule is larger

and lighter than water, it envelops around each soil particle and makes the cation exchange unavailable. It also helps fill any voids in the soil profile.

Polyethylene, vinyl and butyl rubber membranes, when properly installed, can be used to prevent seepage. The membranes must be protected from puncture during installation and use. Secure the lining by burying the top 0.2–0.3 m in a trench 0.2–0.25 m deep and approximately 0.3 m wide. The trench must be located above the usual waterline. Because of their weakness, all polyethylene and vinyl membranes should be protected from damage by a cover of earth not less than 0.2 m thick. Butyl rubber membranes need not be covered unless the area is subject to damage by livestock or to danger from puncture by swimmers or fishermen. To protect against livestock, swimmers and fishermen, a minimum of 0.25 m of earth or a mixture of earth and gravel should cover all types of membranes. The bottom 0.1 m should be no coarser than fine sand. All earth covers must be free of large clods, sharp rocks, sticks and other objects that could puncture the membrane, and they must be carefully placed.

Conclusions

Sinkholes are a surface symptom of often complicated subsurface erosion processes. Although they vary in sizes, shapes, and types, water activities are the dominant enabling forces for their formation. Proper land use in sinkhole-prone areas should include a sinkhole management plan that prevents new sinkhole from occurring and avoids groundwater contamination. Various techniques are available for sinkhole repairs, and their choice depends on the physical, hydrological and ecological properties of the sinkhole and tolerance of the construction to collapse or subsidence. The engineering measures need to be tailored to address the specific conditions of the sinkhole to be repaired. In general, a sinkhole remediation consists of plugging of the throat, filling of the void and capping. When the sinkhole is improved to continue to drain surface runoff, it may be necessary that both the water quality and quantity need to be addressed.

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