Induced and Natural Sinkholes in Alabama–A Continuing Problem Along Highway Corridors

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Sinkholes are divided into two categories, induced (man-related) and natural. Since 1900, an estimated 4000 induced sinkholes or related features have formed in Alabama; fewer than 50 natural sinkholes have been reported. Most induced sinkholes are caused by water-level declines due to pumpage; others result from factors associated with construction. Almost all occur where cavities develop in unconsolidated deposits overlying openings in bedrock. The downward migration of the deposits and the development of the cavities are caused or accelerated by a water-level decline that results in the loss of buoyant support and increases the velocity of water movement, the magnitude of water-level fluctuations, and the induced recharge. Most sinkholes caused by construction are due to the diversion of drainage over openings in bedrock. Many natural sinkholes are caused by the collapse or downward migration of unconsolidated deposits into openings in bedrock. The downward migration that sometimes creates cavities in the deposits results from natural declines in the water table, progressive enlargement by solution of openings in the top of bedrock, or a combination of both. The failure of bedrock roofs over solutionally enlarged openings is a rare occurrence. The time required for the development of natural sinkholes is far greater than that associated with induced sinkholes.

Sinkholes formed by collapse of the land surface have caused a variety of problems related to the maintenance and safety of structures and the pollution of existing and potential water supplies. In Alabama there have been costly damage and numerous accidents as a result of collapses beneath highways, streets, railroads, buildings, sewers, gas pipelines, vehicles, animals, and people.

This report is an attempt to provide engineers with a description of the forces involved in the development of sinkholes so as to aid them in construction over problem areas or in repairing damage resulting from sinkholes. The description of these forces will also aid in the identification of active and potential areas of sinkhole development, which would allow planners to avoid these areas as routes for new highway corridors.

GEOLOGIC AND HYDROLOGIC SETTING

The terrane used here to illustrate sinkhole development is a youthful basin underlain by carbonate rocks such as limestone and dolomite (Figure 1). The basin contains a perennial or near-perennial stream. This particular terrane is used because it is similar to that of 10 active areas of sinkhole development in Alabama. Factors related to the development of sinkholes that have been observed in these areas are generally applicable to other carbonate terranes. The terrane differs from those examined only in the inclination of the beds, which is shown as horizontal for ease of illustration.

The development of sinkholes is primarily dependent on past and present relations between carbonate rocks and water, climatic conditions, vegetation, and topography, and the presence or absence of residual or other unconsolidated deposits overlying the bedrock. The source of water associated with the development of sinkholes is precipitation, which, in Alabama, generally exceeds 1300 mm (50 in) annually. Part of the water runs off directly into streams, part replenishes soil moisture but is then returned to the atmosphere by evaporation and transpiration, and the remainder percolates downward below the soil zone to groundwater reservoirs.

Water is stored in and moves through interconnected openings in carbonate rocks. Most of the openings were created, or existing openings along bedding planes, joints, fractures, and faults were enlarged, by the solvent action of slightly acidic water in contact with the rocks. The water in the interconnected openings moves in response to gravity, generally toward a stream channel where it discharges and becomes a part of the streamflow.

Water in openings in carbonate rocks occurs under both water-table and artesian conditions; however, this study is concerned primarily with that occurring under water-table conditions. The water table is the unconfined upper surface of a zone in which all openings are filled with water. The configuration of the water table conforms somewhat to that of the overlying topography but is influenced by geologic structure, withdrawal of water, and variations in rainfall. The lowest altitude of the water level in a drainage basin containing a perennial stream occurs where the water level intersects the stream channel (Figure 1). Openings in the bedrock underlying the lower parts of the basin are water filled. This con-

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dition is maintained by recharge from precipitation in the basin. The water table underlying adjacent highland areas within the basin occurs at higher altitudes than the water table near the perennial stream. Openings in the bedrock between the land surface and the underlying water table in highland areas are air filled. The progressive enlargement of these openings by solution has resulted in the formation of the caves that are common in some parts of Alabama.

The general movement of water through openings in the bedrock underlying the basin, even though the route may be circuitous, is toward the stream channel and downstream under a gentle gradient approximating that of the stream. Some water moving from higher to lower altitudes is discharged through springs along flanks of the basin at intersections of the land surface and the water table. The velocity of movement of water in openings underlying most of the lowland area is probably sluggish when compared to that in openings at higher altitudes.

A mantle of unconsolidated deposits consisting chiefly of residual clay (residuum), which has resulted from the solution of the underlying carbonate rocks, generally covers most of the bedrock in the typical basin described. Alluvial or other unconsolidated deposits often overlie the residual clay. The residuum commonly contains varying amounts of chert debris that are insoluble remnants of the underlying bedrock. Some of the unconsolidated deposits are carried by water into openings in the bedrock. These deposits commonly fill solutionally enlarged joints, fractures, or other openings underlying the lowland areas. The buried contact between the residuum and the underlying bedrock, because of differential solution, can be highly irregular.

SINKHOLES

Sinkholes can be separated into two categories, in relation to their occurrence, even though most of the factors involved in their development are the same. These categories are defined here as induced and natural. Induced sinkholes are those that can be related to man's activities; natural ones are those that cannot. These categories can generally be separated on the basis of their physical characteristics and environmental setting. The development of all sinkholes, regardless of their category, is dependent on some degree of solution of the underlying bedrock.

This paper is devoted almost entirely to the description of the initial stage of development of both induced and natural sinkholes. New sinkholes of either type are similar in size. Recent collapses forming sinkholes in Alabama generally range from 1 to 90 m (3 to 300 ft) in diameter and from 0.3 to 30 m (1 to 100 ft) in depth. The largest known collapse (Figure 2) occurred in a wooded area in Shelby County in December 1972, apparently in a matter of seconds, and was about 90 m (300 ft) in diameter and 30 m (100 ft) deep.

Induced Sinkholes

It is estimated that more than 4000 induced sinkholes, areas of subsidence, or other related features have occurred in Alabama since 1900. Most of them have occurred since 1950. These sinkholes are divided into two types: those related to a decline in the water table, and those related to construction.

Decline of the Water Table

The relation between the formation of sinkholes and high pumpage of water from new wells was recognized in Alabama as early as 1933 (1). Subsequent studies (2, 3, 4, 5) have verified this relation. Collapses have occurred in the immediate vicinities of 36 wells tapping limestone and dolomite formations in Alabama. The actual number of wells related to collapses probably exceeds this figure, but no inventory has been attempted. Three collapses that occurred during a pumping test of a new well in Birmingham in 1959 are excellent examples of sinkholes resulting from man-created forces (4).

Dewatering or the continuous withdrawal of large quantities of water from carbonate rocks by wells, quarries, and mines in numerous other areas in Alabama is associated with extremely active sinkhole development. The numerous collapses in these areas contrast sharply with their rarity in adjacent geologically and hydrologically similar areas where withdrawals of water are minimal. For example, in five active sinkhole areas, there are an estimated 1700 collapses, areas of subsidence, or other associated features, which have a total combined area of about 36 km^2 (14 $miles^2$). There are few recent collapses in adjacent areas underlain by the same geologic forms. This phenomenon is not unusual; the relation of this type of sinkhole occurrence to cones of depression created by water withdrawals in Pennsylvania and Africa has been well established (6, 7).

Two areas in Alabama in which intensive sinkhole development has occurred and is occurring have been studied in detail. Both areas became prone to the development of sinkholes by major declines of the water table due to the withdrawal of groundwater. The formation of sinkholes in both areas resulted from the creation and collapse of cavities in unconsolidated deposits (4, 5).

Cavities in unconsolidated deposits overlying carbonate rocks in areas of Africa and Pennsylvania where there have been water-table declines have also been described and explored (7, 8, 9). The growth of one such cavity in Birmingham has been photographed through a small adjoining opening (10). The growth of this cavity resulted from the downward migration of clay into two small openings in the top of the bedrock.

Previous reports have associated the development of sinkholes and subsidence with subsurface erosion caused by pumpage, the position of the water table, or lowering of the water table due to withdrawals of groundwater. Johnston (1) has noted that sinkholes appear to be caused by the removal by moving groundwater from the residual clay filling in fissures of the limestone. He described the stoping action and surmised that the water would have to be moving fast enough to erode the clay and that, because of this, there appeared to be a causal relationship between this type of sinkhole and high pumpage from new wells. Robinson and others (2) have attributed the development of sinkholes in a cone of depression to the increased velocity of groundwater, which caused the collapse of clay and rock-filled cavities in bedrock.

Foose (6) associated the occurrence of recent sinkhole activity with pumping and the subsequent decline of the water table. He determined that formation of sinkholes was confined to areas where a drastic lowering of the water table had occurred, that their occurrence ceased when the water table recovered, and that the shape of recent collapses indicated a lowering of the water table and the withdrawal of its support.

Jennings and others (9) have associated development of sinkholes with pumpage and the creation of cones of depression. They found that sinkhole and subsidence problems increased where the water table was lowered, and described the formation, enlargement, and collapse of cavities in unconsolidated deposits that had migrated downward. They also described the geologic conditions necessary for the formation of the cavities. Foose (7), in addition to his previous findings (6), has described the development of cavities in unconsolidated deposits in Africa and attributed it to the shrinkage of desiccated debris and the downward migration of the debris into bedrock openings. He has also outlined geologic conditions related to cavity development and found that a lowering of the water table initiated their formation.

Previous reports have described only indirectly or in part the hydrologic forces that result from a decline in the water table and create or accelerate the growth of cavities that collapse and form sinkholes. These forces are (a) loss of support to roofs of cavities in bedrock that had been previously filled with water and to residual clay or other unconsolidated deposits overlying openings in the bedrock, (b) an increase in the velocity of movement of the groundwater, (c) an increase in the amplitude of water-table fluctuations, and (d) the movement of water from the land surface to openings in the underlying bedrock where recharge had previously been rejected because the openings were water filled.

The same forces that create cavities and subsequent collapses also cause subsidence. The movement of unconsolidated deposits into bedrock, where the overlying material is not sufficiently strong to maintain a cavity roof, will result in subsidence at the surface (8). Subsidence can also result from consolidation or compaction due to the draining of water from deposits previously located beneath the water table (11). Recognizable subsidence sometimes precedes a collapse (4). This occurrence, if the unconsolidated deposits are thin and consist chiefly of clay, indicates that the subsidence is due to a downward migration of the deposits rather than to compaction.

The forces that result in the development of cavities and their eventual collapse are shown in a schematic diagram (Figure 3) that illustrates the changes in natural geologic and hydrologic conditions previously described and shown in Figure 1.

The effects of the forces triggered by a lowering of the water table are basic and can often be observed, measured, estimated, or computed in hydrologic work.

The loss of buoyant support that follows a decline in the water table can result in an immediate collapse of the roofs of openings in the bedrock or can cause a downward migration of unconsolidated deposits overlying openings in the bedrock. The buoyant support exerted by water on a solid (and hypothetically) unsaturated clay overlying an opening in bedrock, for instance, would be equal to about 40 percent of its weight, based on the specific gravities of the constituents involved. Site 1 of Figure 1 shows an unconsolidated deposit overlying a water-filled opening in bedrock; site 1 of Figure 3 shows the decline in the water table, and the resulting cavity in the deposit after the downward migration of the unconsolidated deposit that was caused by the loss of support. The cavity may then remain stable or it may enlarge upward by the spalling of the overlying deposit until the roof collapses.

The creation of a cone of depression in an area of water withdrawal results in an increased hydraulic gradient (slope of the water table) toward the point of discharge and a corresponding increase in the velocity of the movement of water. This force can result in the flushing out of the finer grained unconsolidated sediments that have accumulated in the interconnected solutionally enlarged openings. It also transports to the point of discharge or to a point of storage in openings at lower altitudes the unconsolidated deposits migrating downward into bedrock openings.

The increase in the velocity of groundwater movement also plays an important role in the development of cavities in unconsolidated deposits. Erosion caused by the movement of water through unobstructed openings and against joints, fractures, faults, or other openings filled with clay or other unconsolidated sediments results in the creation of cavities that enlarge and eventually collapse (1, 2). Collapses and subsidence due to erosion of clay-filled, solutionally enlarged openings are occurring beneath and near Interstate 59 in Birmingham.

Pumpage results in fluctuations in groundwater levels that are of greater magnitude than those occurring under natural conditions. The magnitude of these fluctuations depends principally on variations in water withdrawal and in natural recharge (precipitation). The repeated movement of water through openings in bedrock against overlying residuum or other unconsolidated sediments causes a repeated addition and subtraction of support to the sediments and repeated saturation and drying. This might be best termed erosion from below because it results in the creation of cavities in unconsolidated deposits, and their enlargement and eventual collapse. Fluctuations of the water table against the roof of a cavity in unconsolidated deposits near Greenwood, Alabama, have been observed and photographed through a small collapse in the center of the roof. These fluctuations, in conjunction with the movement of surface water into openings in the ground, created the cavity and have caused its collapse (5).

A drastic decline of the water table in a lowland area (Figure 3) in which all openings in the underlying carbonate rock were previously water filled (Figure 1) commonly results in induced recharge from surface water. This recharge would have been rejected prior to the decline because the underlying openings were water filled. The quantity of surface water available as recharge to such an area is generally large because of the runoff moving to and through it from areas at higher altitudes.

The inducement of surface water infiltration through openings in the unconsolidated deposits interconnected with openings in the underlying bedrock results in the creation of cavities where the material overlying the openings in the bedrock is eroded to lower altitudes. Repeated rains result in the progressive enlargement of this type of cavity, and a corresponding thinning of the cavity roof due to this enlargement eventually results in a collapse. The position of the water table below unconsolidated deposits and openings in bedrock that is favorable to induced recharge is illustrated in Figure 3. Sites 2, 3, and 4 illustrate a collapse and cavities in unconsolidated deposits that were formed primarily or in part by induced recharge. The creation and eventual collapse of cavities in unconsolidated deposits by induced recharge are the process described by many authors as piping or subsurface mechanical erosion; the term has been applied mainly to collapses occurring in noncarbonate rocks (12).

In an area of sinkhole development where a cone of depression is maintained by constant pumpage (Figure 3), all of the forces described are in operation even though one may be principally responsible for the creation of a cavity and its collapse. For instance, the inducement of recharge from the surface (site 2 in Figure 3), where the water table is maintained at depths well below the base of unconsolidated deposits, can be solely responsible for the development of cavities and their collapse. In contrast, a cavity resulting from a loss of support (site 1 in Figure 3) can be enlarged and collapsed by induced recharge if it has intersected openings interconnected with the surface. In an area near the outer margin of the cone (site 4 in Figure 3), the creation of a cavity and its collapse can be the result of several forces. The cavity can originate from a loss of support; could be enlarged by continuous addition and subtraction of support and the alternate wetting and drying resulting from water-level fluctuations; could be enlarged by the increased velocity of movement of water; or could be enlarged and collapsed by water induced from the surface.

Construction

Collapses resulting from construction are far less numerous than those due to a decline in the water table; however, they have resulted in extensive damage. In this paper, the term construction applies not only to the erection of a structure, but also to any diversion of natural drainage, and includes the clearing of timber in rural areas.

The simplest cause of sinkholes or subsidence resulting from construction is loading. The emplacement of weight on unconsolidated deposits alone can result in compaction. The compaction can be irregular if the deposits overlie an uneven bedrock surface or openings in the bedrock, and the differential compaction and accompanying subsidence can result in foundation problems. The presence of natural or induced cavities in bedrock or unconsolidated deposits may result in a collapse when the overlying roof is subjected to loading.

Construction on unconsolidated deposits that overlie air-filled openings in bedrock (site 5 in Figure 1) can result in the formation of a sinkhole (site 5 in Figure 3). In highway or other construction, grading and the removal of trees create new openings that connect the land surface with openings in bedrock. The concentration of surface runoff in drains or impoundments increases the downward movement of water. This downward movement sometimes erodes and transports unconsolidated deposits into underlying openings in bedrock, forming a cavity in the deposits that eventually enlarges and collapses. This process is the same as that described under induced recharge (piping) where the water table has been lowered by pumping. It has also been described and illustrated in a carbonate terrane in Alabama where collapses have resulted in retention-basin failures (13).

The diversion of drainage, followed by the development of cavities and a tunnel in sand overlying carbonate rocks near Centerville, Alabama, illustrates the piping process well. The grading of a timber trail caused the diversion and discharge of water into an opening at the surface (Figure 4) that interconnected with an opening in the underlying bedrock. The water moved downward about 9 m (30 ft) and laterally about 15 m (50 ft), and then discharged downward. A cavity developed at this point, and, with continued subsurface erosion, the route along which the water moved enlarged backward toward the surface forming a tunnel. A second cavity then formed as the erosion approached the surface and the collapse of its roof enlarged the opening into which water discharged.

Piping action can also be the mechanism for the development of sinkholes in places where water has been impounded on unconsolidated deposits that overlie carbonate rocks containing water-filled openings. On the floor of the impoundment, water moving through openings in the unconsolidated deposits to openings in the carbonate rocks can form and collapse cavities in the deposits. This process generally occurs where there is a considerable head or pressure exerted by the impounded water and where openings in the carbonate rocks have a discharge point outside of the impoundment at a lower altitude. The increase in the velocity of the impounded water moving through unconsolidated deposits to underlying openings in the bedrock will have an erosive capacity similar to that described previously in a cone of depression caused by pumpage. The saturation of previously unsaturated unconsolidated deposits by the impoundment will also enhance the downward transport of the deposits. This action is probably responsible for the formation of sinkholes in the impoundment behind Logan Martin Dam on the Coosa River, which reportedly resulted in the discharge of muddy water from an opening in the stream channel outside of the impoundment.

A damaging collapse due to construction involved Interstate 59 near Attalla, Alabama. A collapse about 3 m (10 ft) in diameter in a drainage ditch along the highway allowed surface drainage to enter the ground. The drainage discharged at a lower altitude beneath the fill of a lower lane, and the lubrication of residual clay underlying the lane by this discharge and some additional water from an unidentified source resulted in a landslide and subsequent highway failure.

Natural Sinkholes

Topographic maps of areas in Alabama show thousands of natural sinkholes. None of these are at the earliest stage of their development. The occurrence of new natural sinkholes is rare. Fewer than 50 of the collapses that were observed resulted in new natural sinkholes, and it is probable that a significant number of these were related in part to man's activities. (This number does not include the collapses that commonly occur inside of or along rims of existing mature sinkholes.)

The development of a new natural sinkhole may reflect displacement of the bedrock, or of the unconsolidated deposits overlying it, or both. The displacement of either or both is generally triggered by progressive solution of bedrock, by a natural decline in the water table, or by a combination of the two. The relations among progressive solution, a decline in the water table, and the accompanying failures of bedrock and unconsolidated roofing is illustrated in Figure 5. The role of solution in the development of natural sinkholes is recognized by all investigators. The effect that solution of bedrock or a decline in the water table has on unconsolidated deposits is not nearly as well defined.

Cavities in unconsolidated deposits overlying carbonate rocks in areas remote from groundwater withdrawals are identical to those resulting in induced sinkholes. This type of cavity eventually results in a natural sinkhole. These cavities have been drilled or augered near Piedmont in Calhoun County, west of Talladega in Talledega County, and near Stevenson in Jackson County. The development of natural sinkholes caused by temporary natural declines in the water table is similar to the occurrence of induced sinkholes caused by pumpage, as shown by the sudden appearance of natural sinkholes during prolonged periods of drought. The most recent prolonged drought in Alabama occurred during the early and middle 1950s, and during this period, notable natural sinkhole development occurred in Limestone, Talladega, and Shelby Counties.

Decline of the Water Table

A major factor responsible for the degradation of a carbonate terrane by solution is the lowering of the base level of a perennial stream as it affects the water table and groundwater discharge (14). Recent natural sinkhole activity along the Flint River in southwest Georgia has been related to the entrenchment of the stream that resulted in a lowering of base level (14). The downward migration of unconsolidated deposits due to the declines in the water table that accompanied a lowering of the base level is considered here to be closely related to the solution process. Major differences between the formation of natural sinkholes resulting from collapses in bedrock and from collapses in unconsolidated deposits are the times required for each to develop and the size and type of opening required for their formation. The time required for a cavity to form in unconsolidated deposits due to changes in the hydrologic regimen in the carbonate terrane described here (Figure 1) could be extremely short as compared to that required for the enlargement by solution of a cavity in bedrock to the point where its roof becomes incompetent. A relatively large cavity in the unconsolidated deposits can also form over a small opening in underlying bedrock.

Natural declines in the water table in Alabama, with the exception of temporary ones caused by prolonged droughts, are chiefly attributable to a lowering of the base level of perennial streams. The lowering of the water table in a stream basin occurs when the stream entrenches or erodes to a lower altitude or when the basin is captured by an adjacent stream having a lower base level. The water table in the basin can also be lowered by an increase in permeability resulting from solution of bedrock (15) or by a permanent climatic change.

Many natural sinkholes in Alabama have resulted from the same kinds of forces that cause induced sinkholes. These forces result from loss of support, increase in velocity of movement of water, water-level fluctuations, and induced recharge. The role that each

Figure 1. Schematic cross-sectional diagram of basin showing geologic and hydrologic conditions.

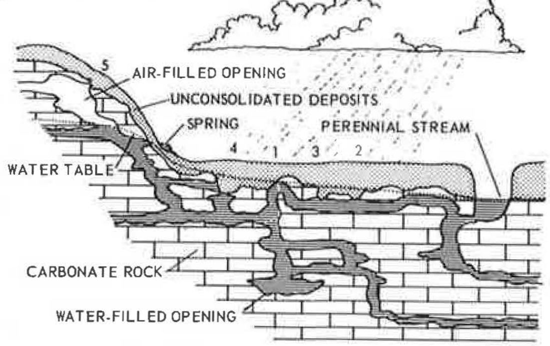


Figure 2. Sinkhole resulting from collapse near Calera in Shelby County.

Figure 3. Schematic cross-sectional diagram of basin showing changes in geologic and hydrologic conditions resulting from water withdrawal.

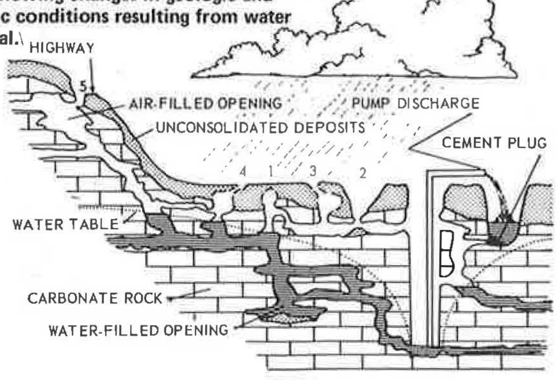
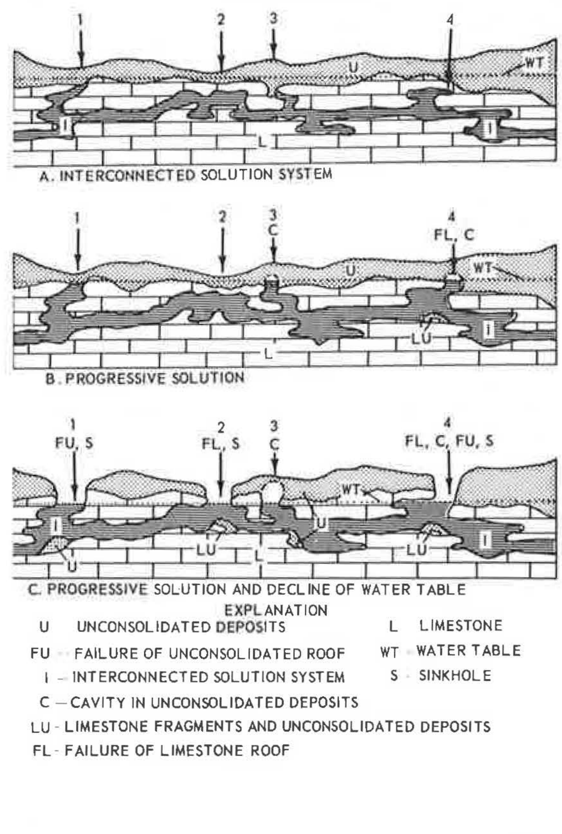


Figure 4. Opening into which water discharges.

Figure 5. Natural sinkhole development.



plays in the development of a sinkhole has been described in detail, and to avoid repetition, only general comments on the relation of these forces to natural sinkhole development are given here. The major difference in the development of induced and natural sinkholes resulting from these forces is the much greater time span involved in a natural lowering of the water table and the formation of natural sinkholes. Forces resulting from natural declines in the water table are much more subtle than those resulting from man-created declines.

A decline in the water table due to the entrenchment of a stream results in an increase in the hydraulic gradient toward the stream and a corresponding increase in the velocity of movement of the water. This increase in velocity would generally be much less than that resulting from most man-related declines because the hydraulic gradient would be more gentle than that resulting from pumpage. The increase would, however, actuate the same processes that cause induced sinkholes.

Water-level fluctuations that cause or contribute to the development of natural sinkholes can occur where openings in bedrock were previously water filled (Figure 1). When the rate of water-level decline exceeds the rate of deepening of the residuum-bedrock contact, the physical situation becomes more conducive to cyclic wetting and drying and the continued addition and subtraction of buoyant support to the residuum.

A natural decline in the water table in lowland areas of the type described (Figure 1) also results in induced recharge. Locally, the quantity of water moving to openings in the bedrock exceeds the recharge prior to the decline, and the water moving through openings at the surface to openings in the bedrock would no longer have its direction of movement affected or its velocity impeded by a water table located above bedrock.

Solution

The solution of carbonate rocks in the terrane shown in Figure 1 precedes the occurrence of sinkholes and is ultimately responsible for their development. The description here is oriented toward the initial stage of development of a natural sinkhole that results from solution alone. The time required for the development of such a sinkhole far exceeds that required for those resulting from other causes. Determining the rate of solution of the bedrock involved in this process is beyond the scope of this report; however, a summary of estimates by previous workers, described by Sweeting (16), indicates that rates of solution for most terranes are considerably less than 100 mm (4 in)/1000 years.

Solution of near-surface bedrock in the basin of a perennial stream is continuous. The overlying soil zone is a principal source of carbon dioxide and minerals from which the water percolating downward derives most of its acidic properties. In lowland areas the upper surface of the carbonate rocks is being degraded by solution, and openings in the bedrock beneath it are being progressively enlarged. Openings connecting the upper surface of the bedrock to the deeper solution system are being created or enlarged by groundwater from below and by surface water moving into the system through the overlying soil zone.

A well-established generalization is that solution action tends to enlarge the moderately large openings in the path of the bulk flow of groundwater at a faster rate than the small openings not in the path of bulk flow (17). This preferential solution will also apply to the upper surface of bedrock. In the terrane described here, the contact between bedrock and unconsolidated deposits is irregular; consequently, the water table may be above bedrock in some places and below it in others (Figure 1). Water percolating through unconsolidated deposits that comes in temporary contact with bedrock on highs above the water table would move toward the lows below the water table where solution is continuous.

Where highland areas bounding a basin are underlain by air-filled cavities in bedrock, a similar enlargement of openings is occurring at a slower rate than that in the lowlands because of the smaller volume of water coming in contact with bedrock after percolating downward through the soil zone. Most large openings beneath the highlands are older than are those underlying lowland areas in the basin. Most of their enlargement probably occurred when they were located in closer proximity to the water table.

Roofs over openings in bedrock can consist of bedrock or of residuum and other unconsolidated deposits, and solution enlargement of them may result in their collapse. Many openings in bedrock, which have been observed from exposures in quarries and data for wells, are filled with residuum or other sediments, but others are not. Openings in the top of bedrock in the type of basin described (Figure 1) are numerous although natural sinkholes are uncommon. More than 50 such openings were exposed in a 1.5-ha (3.7-acre) tract in Shelby County where unconsolidated deposits were removed to permit the bedrock to be washed clean by precipitation. It is apparent from the scarcity of natural sinkholes or recognizable subsidence prior to pumpage in areas such as that shown in Figure 1 that either many bedrock openings have been filled with sediments or the deposits overlying the openings are capable of supporting themselves.

Natural subsidence that has occurred over openings in bedrock in the basin described and shown in Figure 1 may have been leveled by the infill of sediments eroded from higher adjacent areas or by deposition of sediments by floods in low areas adjacent to streams. The collapse of unconsolidated deposits forming a roof over an opening in bedrock will occur when the opening is progressively enlarged by solution until the overlying deposits cannot support their weight. The enlargement of an opening that precedes the collapse is illustrated at site 1 in Figure 5. If an opening is filled with clay or other sediments, subsidence or a collapse will occur where solution progresses at a rate greater than the deposition required to maintain a level land surface.

The collapse of the bedrock roof of an opening that has been progressively enlarged by solution occurs when the roof can no longer maintain its integrity. The progressive enlargement of such an opening and the resulting roof failure are illustrated at site 2 in Figure 5. This occurrence is generally considered to be rare (18, 19). However, it may be more common than has been indicated because cavities similar to those in unconsolidated deposits associated with induced and natural declines in the water table undoubtedly result also from the collapse of bedrock roofs. A collapse of a thin but small part of a bedrock roof over an opening would, in many instances, result in a cavity in the overlying unconsolidated deposits due to their downward migration into the bedrock. Enlargement of the cavity would eventually result in a collapse at the surface that might not be interpreted as bedrock failure. The enlargement of an opening by solution, a failure in its roof resulting in a cavity in overlying unconsolidated deposits, and the resulting sinkhole are shown at site 4 in Figure 5.

In areas underlain by air-filled openings (caves), the enlargement of cavities by downward-percolating water would be expected to cause the eventual collapse of bedrock roofs. Sinkholes attributable to this mode of occurrence have been identified by Howard (19). Collapses resulting from enlargement of openings in carbonate rocks overlain by sandstone and thin-bedded limestone have also been identified (18, 20).

Where air-filled openings in bedrock are overlain by unconsolidated deposits, the initial development of some sinkholes can be attributed to downward migration caused by inflow and infiltration of surface water; a cavity then forms in the deposits. This mode of development is the same as that resulting from the downward movement of surface water where it is responsible for induced sinkholes. These collapses generally occur in intermittent streambeds but can occur elsewhere.

Solution of the upper surface of the bedrock has long been recognized as a mode of development of sinkholes. In this case, the topography reflects the upper surface of the bedrock. In relating the probability of this mode of development to some broad and shallow sinkholes in Kentucky, Walker (21) has described the process as follows:

When the surface of bedrock dissolves, the insoluble residue occupies only about one-tenth of the space the rock did; open space would develop except that the soil mass slumps downward and the surface with it. Solution proceeds faster at some places than at others because the rock is more soluble or joints are more closely spaced, and slight depressions appear. Once formed, the depressions tend to grow larger because local surface runoff collects in them, and more water then seeps down to attack the bedrock under them than elsewhere in the vicinity. Solution concentrated at the center finally brings about the infall of soil blocks and the development of a swallow hole.

Solution of the upper surface of carbonate rocks will result in the development of sinkholes in the terrane described here. Most sinkholes, however, will result from the solution enlargement of existing openings in the top of the bedrock surface to eventually cause displacement of overlying unconsolidated deposits. This process of enlargement and displacement is also illustrated at sites 1 and 3 of Figure 5. Surface depressions resulting from solution of bedrock where it contains no openings would probably be rare in this terrane as deposition of sediments eroded from flanks of the basin (Figure 1) or from flooding would tend to level depressions of this type. This process is indicated by the lack of surface expression over many irregularities in the top of the bedrock in basins in Jefferson County, and is similar to effects described by Coleman and Balchin (22) and Howard (19). In the terrane described here (Figure 1), it would be difficult to distinguish sinkholes resulting from solution of the upper surface of bedrock from others resulting from the progressive solution of openings in the top of bedrock that are interconnected with other openings in the subsurface. Solution of the upper surface of carbonate rocks, however, plays an integral part in the development of large, shallow sinkholes in the more mature carbonate terranes in Alabama.

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