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Corrective Procedures for Sinkhole Collapse on the Western Highland Rim, Tennessee

PHILLIP R. KEMMERLY

ABSTRACT

Sinkhole collapse poses an increasing problem for the engineer and geologist. This is partly because no systematic procedure exists for repairing such collapses. Any successful repair procedure for use in the karst limestones of middle Tennessee should include efforts to identify and control water movement into the collapse site. A geologically based approach to collapse repair that takes advantage of the causal and correlative factors responsible for nearly 100 collapses in the study area and an extensive fluorescein dye-tracing program are described. Corrective procedures deal not only with the collapse itself but with the rerouting, to the extent possible, of runoff and groundwater at the collapse site. A high-permeability, graded rock fill is placed in the collapse, and water movement into the site is minimized.

Karst topography in general poses several highway engineering problems, the most serious of which is collapse. Within the last decade, contract costs for correcting sinkhole collapses involving bridges and highways in Tennessee and Alabama exceeded $10 million unadjusted for inflation (1). Significant progress has been made in the last decade in identifying the geologic and hydrologic factors and construction practices that contribute to sinkhole collapse (2,3). Field research to date deals primarily with recognition, detection, and prediction of sinkhole collapse (4,5). Little published work deals with correcting sinkhole collapse.

Sinkhole collapse is defined here as the nearly vertical downward movement of some portion of either the bottom or flank slope of the karst depression, along a defined failure surface, into an underlying void (cavity, solution-enlarged joints, or joint intersection).

A geologically based engineering approach to correcting collapse in the karstic limestones of the Western Highland Rim of Tennessee is described. Primary emphasis is on recognizing and effectively countering the geologic and hydrologic factors responsible for collapse. Secondary emphasis is on a collapse repair technique. Careful attention to surface and subsurface geologic and hydrologic conditions at the collapse site should ensure successful repair efforts.

GENERAL GEOLOGIC SETTING

The karst topography of the northern part of the Western Highland Rim is developed on the gently dipping west-northwest flank of the Nashville Dome (Figure 1). Dominant karst landforms include dolines (sinkholes), disappearing streams, and an extensive cave network. The karst landscape is underlain, from oldest to youngest, by Warsaw, St. Louis, and Ste. Genevieve limestones (formations). Karstification is most evident in the St. Louis and Ste. Genevieve limestones, particularly where these crop out north and east of the Cumberland River. Table 1 gives a generalized geologic description of the karst units for engineering use.

The carbonate bedrock underlying the study area has three major joints sets oriented N70°E to N80°E, N20°E to N40°E, and N20°W to N30°W. The bedrock dips about one-half of a degree to the northwest. Joints in the bedrock play a primary role in controlling groundwater movement. The low-angle dip of the bedrock to the north and northwest is a secondary factor influencing groundwater movement.

The limestones of the study area differentially weather into clayey, cherty residuum. This residuum typically consists of 0-70 ft of highly weathered, buff to red, angular to blocky, porous chert pebbles and cobbles incorporated in a yellow to red highly mottled clay matrix (CH-CL). The extent and particle-size distribution of the chert vary within and be-

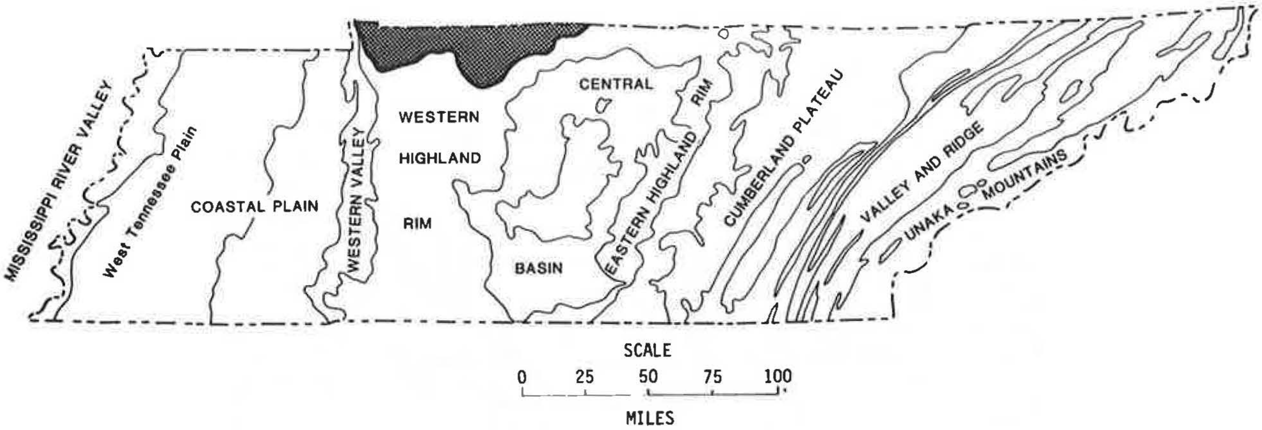

FIGURE 1 Physiographic map of the karst area of the Western Highland Rim.

TABLE 1 Generalized Geologic Description of Karst Units for Engineering Use

Formation	Characteristics	Karst Expression (sinkholes/ square mile)	Collapse Risk
Ste. Genevieve limestone	Gray to yellow-brown, fine- to coarse-grained, thin- to thick-bedded, thickness: 0-90 ft	0-25	Moderate to severe, particularly on uplands near Red River
St. Louis limestone	Brownish-gray to yellowish-brown, fine- to coarse-grained, thin- to thick-bedded, thickness: 0-200 ft	0-40	Moderate to severe
Warsaw limestone	Brownish-gray to yellowish-brown, fine- to coarse-grained, thin- to very thick-bedded, thickness: 0-200 ft	0-5	Low

tween the residuum units derived from each formation.

Loess, composed of brown to tan silt (ML-MH), caps many hilltops and some gently sloping surfaces surrounding many karst depressions north of the Cumberland River. The loess is up to 4 ft thick. Under the influence of gravity, loess is transported downslope by sheet wash and channelized flow, resulting in the mixing of loess with the underlying residuum. This mixing produces a third unconsolidated unit--silty colluvium. The silty colluvium consists of 0-15 ft of brown to tannish yellow clayey silt (ML-CL) within which occur minor quantities of sand- and pebble-sized chert derived from the underlying residuum.

All of the nearly 100 collapses examined in the study area occurred in the soil overlying solution-enlarged joints in the bedrock. The boundary or contact between the soil and bedrock can best be termed pinnacle in nature. Soil-bedrock contacts in the area have a depth-to-bedrock variation so great that 10 to 40 ft of difference in the depth to soluble rock is common at sites less than 50 ft apart horizontally.

GENERAL HYDROLOGIC SETTING

The general hydrologic setting is one of the most important factors affecting the stability of karst depressions. Drainage is principally in the subsurface and consists of an interconnected system of caves, enlarged vertical fractures, and smaller cavities developed along bedding planes. The open joints (vertical fractures) in the carbonate rock extend downward from the surface and are open in varying degree to at least the elevation of the bedrock channels beneath the alluvium of the Cumberland and Red rivers. The Cumberland River serves as the major discharge point for groundwater moving in the subsurface.

The water table surface, to the extent it exists in the study area, neither closely "mimics" the landscape, nor is it always laterally continuous (Figure 2). The well-developed fracture system in the limestones; the great variation in fracture permeability within the joints, caves, interconnecting passages, and bedding planes; and fluorescein dye tests suggest that an open groundwater system exists in the karst terrain of the Highland Rim.

Fluctuations in groundwater levels are of special interest because of their observed effect on the shear strength of the soil occupying the voids in jointed rock and bridging the pinnacles along the soil-bedrock contact. Fluctuations in the local water table are of two general kinds--seasonal and pulse. The water table drops during late summer and early fall and rises in late winter and early spring. Pulse loadings, from a single storm event or series of storm events, locally can trigger a rise in static water level of as much as 10 to 50 ft above its elevation before the storm events. Rapid fluctuations occur in areas where the system is less open and groundwater movement is restricted to smaller joints and fewer solution cavities. The greater the fracture permeability in a localized area, the smaller will be any local groundwater level fluctuations.

Sinkholes in the area play a dual role. First, the sinkhole acts as a collecting basin for runoff. Second, surface water, collected in the depression, drains vertically through the residuum into bedrock fractures and downward to recharge the water table. The water table is directly connected to the Cumberland and Red rivers by seeps and springs associated with solution openings above and below river level.

Field data plus limited data from other sources

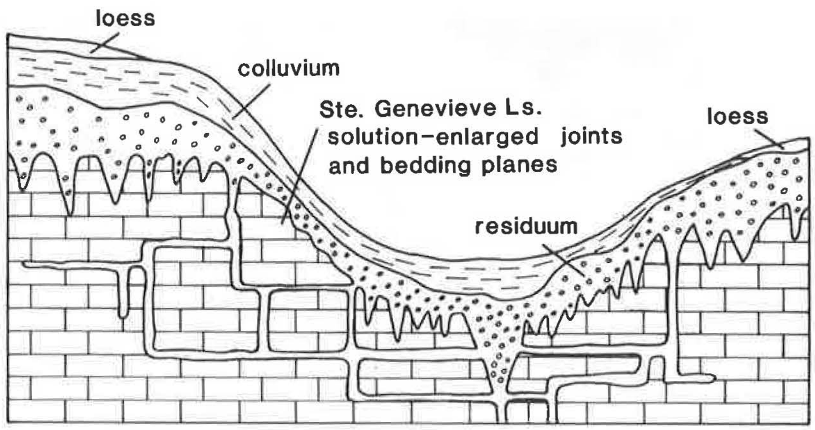

FIGURE 2 General geologic conditions controlling groundwater occurrence in the study area.

(6-8) indicate that water as well as air may be found in some joints and small cavities along bedding planes. Significant quantities of groundwater do occur in the clayey chert-rubble zones that mark the very irregular and pinnacled soil-bedrock contact. A water table occurs near the top of the carbonate bedrock and will also appear in the cherty clay residuum where these deposits are particularly thick along the very irregular soil-bedrock contact. The local water table has a low hydraulic gradient during most of the year. Rapid increases in the hydraulic gradient occur locally in the study area during periods of heavy or prolonged precipitation when recharge through sinkholes exceeds the ability of the groundwater system to transmit it, via springs, to the Cumberland and Red rivers. Water, moving along the most open fractures and bedding planes in the general direction of the dip of carbonate bedrock, is locally forced under excessive hydraulic head to back-flood the nearest available solution-enlarged joints or joint intersections. Substantial volumes of groundwater collect where joints and bedding planes intersect major solution-enlarged joint sets. The water, temporarily forced to rise upward and laterally through solution-enlarged joints and bedding planes, frequently encounters solution openings containing sediment. Core samples from such settings have shown the sediment to be saturated, soft, and weak. The extent of this back-flooding is primarily a function of joint permeability and hydraulic head. Back-flooding is a short-lived phenomenon. Within hours, or at most a few days, back-flooding of the rock fractures, bedding planes, and caverns is eliminated as a result of base flow into the Red and Cumberland rivers. The hydraulic gradient is then lowered to its pre-storm value.

Groundwater recharge occurs primarily through sinkhole swallets and solution-enlarged joint sets. The amount of recharge taking place directly through the residuum is not known although some soil units have such a high clay content as to preclude significant amounts of recharge. Static water levels in the water table range from 50 to 125 ft below ground level in the study area (7). This wide range reflects the erratic and discontinuous nature of the groundwater system.

COLLAPSE CRITERIA AND MECHANISM

A brief synopsis of the geologic and hydrologic criteria associated with nearly 100 collapses in the study area is given here so the reader can evaluate the remedial measures taken to correct sinkhole collapse. More detailed discussions of these factors can be found elsewhere (4).

All sinkhole collapses occurred in the soil, which exists as a mantle above a pinnacled bedrock surface. Soil thickness varied from 0 to 70 ft, reflecting differences in weathering intensity and the resulting irregularities in the pinnacled soil-bedrock contact. The relation between soil characteristics and sinkhole collapse is largely a function of texture, frequency of wetting, vertical and horizontal permeability, and the cumulative effects that these factors have on the shear strength of the soil.

Collapse sites are underlain primarily by the Ste. Genevieve and St. Louis limestones of Mississippian age. Although more collapses occurred in the soil overlying the Ste. Genevieve than in that over the St. Louis limestone, lithologic differences within bedrock formations appeared as great as the differences between formations, especially in the case of the St. Louis limestone.

Collapse occurrence correlates with three systematic joint sets in the study area (N70°E to N80°E, N20°E to N40°E, N20°W to N30°W). Fifty-eight collapses occurred in sinkholes with a long-axis orientation (bearing of the maximum depression diameter) parallel to the N70°E to N80°E joint set and 30 collapses occurred in karst depressions with a long-axis orientation parallel to the N20°E to N40°E joint set. Nine collapses occurred in sinkholes with a long-axis orientation parallel to the N20°W to N30°W joint set. The N70°E to N80°E joint set showed larger solution openings than either of the other two joint sets. The solution enlargement of the N70°E to N80°E set averaged 1 ft and ranged between 0.25 and 3 ft. The width of the solution-enlarged N70°E to N80°E joint set varied little between the St. Louis and Ste. Genevieve limestones. The tendency for collapse to occur in sinkholes with the long-axis orientation parallel to the N70°E to N80°E joint set reflects the ease with which groundwater migrated along this joint set saturating the soil bridging the solution-enlarged joints.

Depression geometry correlates with collapse. Collapse occurred most frequently in sinkholes with an L/W ratio (maximum depression diameter/minimum depression diameter, measured at right angles to maximum diameter) approaching circularity ($L/W \leq 1.80$). The L/W ratio, before collapse, in part reflected the engineering characteristics (cohesion, angle of internal friction, Atterburg limits) of the soil occupying the void in the carbonate bedrock and the size of the void.

A strong positive correlation exists between monthly collapse rates and the extent to which precipitation deviates (deficits or surpluses) from long-term monthly means. The correlation reflected fluctuating groundwater levels, following periods of precipitation surplus or deficits, in an area noted for large variations in vertical and horizontal fracture permeability.

Differential settlement of the soil along the pinnacled bedrock surface resulted in sediment bridging the rock pinnacles (soil arch). Wetting of the soil-arch sediments by groundwater, locally back-flooding the nearest available joint intersections, reduces the shear strength of the soil arches. Groundwater temporarily back-flooding the joints beneath the soil arch provides a significant vertical stress to support the soil bridging the void in the bedrock, even though wetting lowers the shear strength of the soil. With falling groundwater levels, soil in the arches was no longer supported by this vertical stress. The reduction in the shear strength of the soil arches eventually reached a threshold value (shear stress induced by the weight of soil-arch sediments $\geq$ shear strength of the arch sediments) such that overburden weight could no longer be transmitted to the bedrock pinnacles providing lateral support for the soil arch. With the threshold exceeded, a final spalling of sediments (along the underside of the soil arch) produced sinkhole collapse (Figure 3).

Since the field inventory began in 1973, approximately 60 percent of the nearly 100 collapses have been man induced. None of the collapses was triggered by groundwater withdrawal, in marked contrast with many of the collapses described in Alabama and Florida. Approximately two-thirds of the induced collapses were due to the alteration of surface drainage during residential and commercial development. Approximately one-third of the collapses resulted from artificial fills being placed in karst depressions.

The disruption of surface drainage in a "depression-pocked" terrain to accommodate construction frequently increases collapse risk for reasons related to the hydrologic functions of sinkholes. Karst depressions serve as point sources of groundwater recharge via solution-enlarged joints and bedding planes and as temporary storage basins for runoff. Urbanization frequently results in additional runoff, generated by increased impermeable surface area being rerouted to the nearest sinkhole. Collapse risk increases where the construction site is located along the N70°E to N80°E joint set between the sinkhole receiving the added runoff and the springs discharging the groundwater. The hydraulic gradient steepens between the sinkhole, which serves as the master collecting basin, and the springs after heavy or prolonged precipitation. The increased water volume, recharging the groundwater, moves down the hydraulic gradient as a water pulse. Frequently the solution-enlarged joints and bedding planes cannot effectively transmit the pulse load and back-flooding occurs in the solution-enlarged joints and joint intersections. Repeated back-flooding of the residuum increases the stress levels and redistributes the stresses acting on the soil arches, so that the vertical effective stress component exceeds zero along the underside of the soil arch. A stable effective stress distribution is reestablished by the spalling of the sediment from the underside of the arch (see Figure 3). Collapse occurs if a stable effective stress distribution is not reestablished as a result of spalling.

Even where surface drainage is not changed by urban development, the additional runoff caused by increased areas of impermeable surface can contribute to sinkhole collapse. The ponded water that collects in the depressions adds weight to the soil arch. The ponded water that does not evaporate infiltrates through the silty colluvial and residuum units at rates that range widely because of vertical and lateral differences in permeability. The contact between the residuum and colluvium is not horizontal but generally concave. The concave residuum-colluvium contact is interrupted by relict joints in the residuum that intersect the colluvium; by abandoned swallets; by previous collapse features; and by chert pebbles on the remnant, erosional surfaces developed locally on the cherty, clayey residuum. The infiltrated water, not stored in the chert-rubble zone along the soil-bedrock contact, migrates downward wetting the soil bridging the bedrock

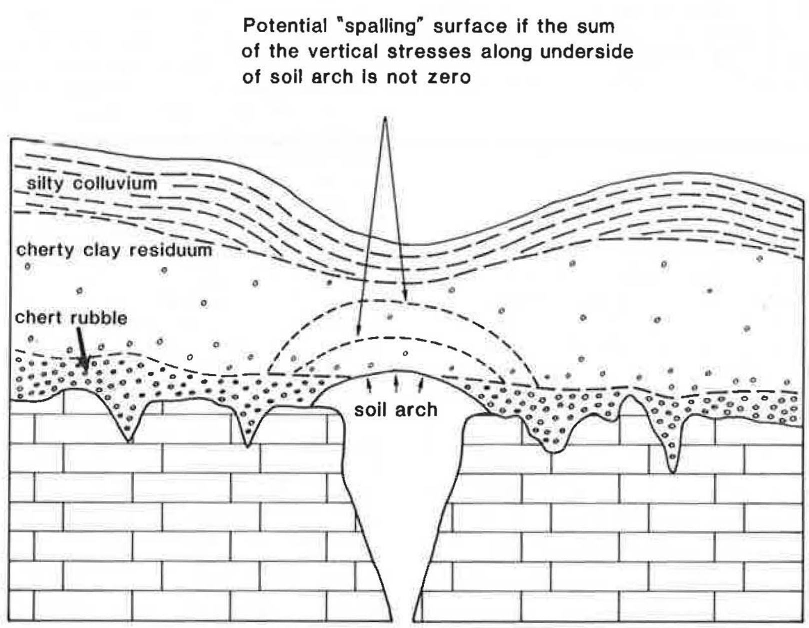

FIGURE 3 Generalized cross section of the soil arch and potential spalling surfaces (dashed lines).

voids. This process is most effective where relict joints are preserved in the residuum. Vertical percolation contributes to sinkhole instability by reducing the cohesive strength of the residuum partly filling the bedrock void. However, this is not as significant a collapse factor as is wetting due to back-flooding of groundwater through fractures beneath the soil arch.

The placement of artificial fill in a sinkhole frequently triggers collapse for reasons directly related to karst processes. The differential solution of the carbonate bedrock produces a thick cherty clayey residuum draped over an exceptionally irregular and pinnacled soil-bedrock contact. The contact surface is made even more irregular by the solution-enlarged joints and the presence of cavities along the soil-bedrock contact. The settlement of the residuum along this irregular contact is uneven resulting in the sagging of residuum into some voids and the bridging of other voids between pinnacles along the contact surface. The soil arches formed where the residuum has sufficient shear strength to bridge the pinnacles are at best unstable, particularly with fluctuations in moisture. Filling the sinkholes results in added stress being applied to the soil arch beneath the surface. The added weight of the fill can result in the accelerated compression of the residuum bridging the void in the bedrock. The added compression increases the bulk density of the soil units disturbing the effective stress distribution within the arch. The added effective stress frequently triggers a spalling of sediment from the underside of the soil arch in an attempt to reestablish equilibrium. Collapse occurs when equilibrium is not reestablished by sediment spalling along the underside of the arch.

Excavation for fill soil near a sinkhole can expose openings in the soil or along the soil-bedrock contact. Any new openings at the surface provide additional routes for direct recharge of groundwater. Rapid downward movement of water has a tendency to erode and transport unconsolidated deposits into the subsurface along solution-enlarged joints. This piping phenomenon can trigger collapse at the surface or initiate cavities in the soil that themselves frequently collapse. Even discounting the piping phenomenon, the added groundwater recharge due to the additional openings produced by grading can compromise the stability of the soil arch by increasing the back-flooding phenomenon that is so closely related to sinkhole collapse in the study area.

CORRECTIVE PROCEDURES

Water is the critical element in any effective collapse repair procedure. A remedial technique that does not include efforts to reroute surface and subsurface water away from the site risks failure.

The first step in the corrective technique requires excavation of the soil within the collapse down to bedrock. The bedrock surface is carefully cleaned to remove as much sediment as possible from the solution-enlarged joints. The Brunton bearing and amount of solution enlargement are measured for all joints exposed in the collapse. The amount of sediment occupying the joints at the site provides important information. Field experience suggests that the greater the solution enlargement and the more sediment-free a joint set is, the greater is the groundwater volume carried by the fractures.

The second step involves a detailed examination of all roadcuts in the area for joints and solution cavities developed along bedding planes. Joint bearings and solution features in the roadcuts are measured and compared with those at the collapse site. Available aerial photographs and topographic maps are examined for evidence of joint control of sinkhole major-axes orientations. The topographic and geologic setting of all springs is identified and correlated with the joint sets for dye-tracing purposes.

Efforts to control groundwater movement through the collapse site require that flow paths be determined if at all possible. Step three in the corrective technique involves an extensive dye-tracing program to locate groundwater flow patterns. Fluorescein ($C_{20}H_{12}O_5$) is best suited for tracing groundwater flow in karst terrains for a number of reasons (9). Fluorescein in groundwater can be detected in the field without a fluorometer. An experienced investigator can frequently detect fluorescein visually. Fluorescein has a higher absorption capacity than rhodamine WT on activated charcoal packets placed in fractures at the collapse site. Most important for field tests, the success of the fluorescein dye tracing is more dependent on the total quantity of dye passing through the activated charcoal packet placed in the joint than on the peak concentration of the dye reaching the collapse site. This fact is particularly important in settings where the fluorescein-charged water must infiltrate through fine-grained soils before entering rock fractures below the surface.

Individual sinkholes in the immediate area of the collapse are charged with a volume of fluorescein dye. Sinkholes with a major axis parallel to the N70°E to N80°E joint set are tested first. Experience shows these joints carry significant groundwater and strongly correlate with collapse. Fluorescein is mixed in an aerated tank in a concentration varying from 1 lb/100 gal (diffuse-flow conditions) to 1 lb/200 gal of water (conduit-flow conditions) depending on whether the dye-charged water is placed directly in an opening (sinkhole swallet) or must infiltrate through the soil. When it reaches the subsurface, the fluorescein-charged water will migrate down the hydraulic gradient with a velocity directly proportional to the gradient. Typical groundwater velocities in the study area are 100-300 ft/hr.

The presence of fluorescein-charged groundwater at the collapse site is detected using activated coconut charcoal packets. The packets consist of 5 in. x 6 in. fine nylon mesh, stapled pads containing two teaspoons of activated charcoal. Each pad is placed upright and perpendicular to the rock fractures exposed in the collapse. The activated charcoal will absorb any fluorescein passing through the packet. The packets should be left in the fractures several hours before they are removed. This gives the fluorescein-charged water the opportunity to reach the collapse if the charged water is being carried to the site from the point of injection. Next, each charcoal packet is emptied into a small container. The charcoal granules are covered with a 5 percent solution of potassium hydroxide (KOH) in 70 percent isopropyl alcohol. Any fluorescein present has been absorbed by the activated charcoal. The KOH in the alcohol replaces the fluorescein which then is released into the alcohol turning the solution a very distinctive yellow-green (a positive test). The process is repeated in each sinkhole until all sinkholes within the immediate area of the collapse are dye tested. The average time for the fluorescein dye to reach the collapse site from a dye-charged sinkhole reflects the direction and slope of the hydraulic gradient as well as the relative secondary permeability of the joint set.

A few days later, a second set of fluorescein dye tests is conducted to determine groundwater movement

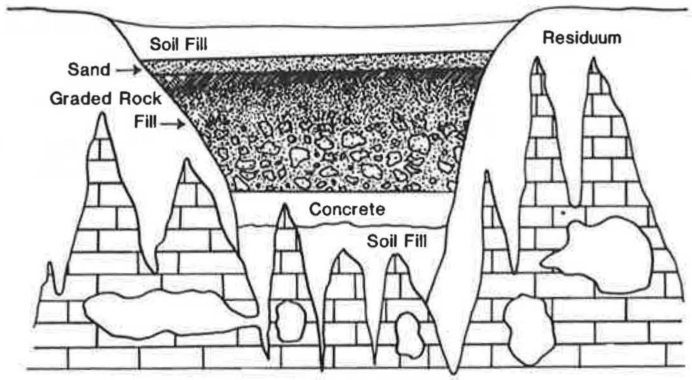

FIGURE 4 Cross section of corrected collapse.

from the collapse to any resurgent springs located earlier. The paths of minimum travel distance to the collapse are plotted on the topographic map for all dye-test sinkholes. Minimum travel plots are also made from the collapse to the resurgent springs serving as discharge points.

Next, a detailed surface-water movement map is prepared to determine which sinkholes are major points of groundwater recharge to the collapse site. Typically, in the study area, the major points of groundwater recharge are the larger, deeper, more structurally aligned (major axis parallel to joint set) sinkholes.

Careful surface grading around the collapse minimizes the volume of surface water recharging groundwater up the hydraulic gradient from the collapse site. Efforts are made to divert surface-water movement into drainage segments or into sinkholes between the collapse site and the resurgent springs or stream (i.e., farther down the local hydraulic gradient). Any groundwater movement would then be down the hydraulic gradient and away from the collapse site. Efforts should be made to reduce the joint permeability at the collapse site because groundwater will, to some extent, continue to move under the collapse site from recharge points outside the immediate area.

High-density concrete is placed in the solution-enlarged joints over a compacted soilfill (CH) placed in the joints to a depth of 1 ft below the top of the rock surface (Figure 4). The concrete is placed inside the solution-enlarged joint overlapping the top to form a plug incapable of entering the joint. The next step involves either using a graded rock filter or a high-density concrete to fill the collapse. In either case, the filter or concrete is placed in the collapse site to within 1 to 3 ft of the surface. Backfill, consisting of an earth fill compacted to a minimum density of 90 percent of the maximum standard AASHTO density, is placed on a sand blanket over the concrete or filter. The compacted controlled fill should allow construction to take place directly over the sinkhole without significant settlement. The ground surface over the collapse site is then graded to slope away from the backfill. Grading the slope away from the backfill prevents water collecting over the repaired collapse.

SUMMARY

A geologically based approach to collapse repair has been developed for use in the karstic limestones of the northern portion of the Western Highland Rim of Tennessee. The technique is based on taking advantage of the significant lithologic, structural, geomorphic, and hydraulic factors found to correlate strongly with collapses in the study area. The technique may not be effective in areas where such geologic and hydrologic factors are not as significant in initiating collapses.

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Use of Sinkholes for Drainage

DAVID L. ROYSTER

ABSTRACT

Sinkholes have long been used for drainage in the design and construction of highways. Decisions to use them, however, seem to be based more on expediency than on engineering and scientific analysis. This practice has apparently resulted from the traditional notion that the processes and mechanisms of sinkhole development and proliferation are not totally analyzable and, therefore, not predictable. Although it is true that investigations of sinkholes and sinkhole-prone topography rarely produce absolute and finite data that can be applied in a strict quantitative sense, there are methods of analysis that, when coupled with experience and judgment, can be used with a high degree of success. In general, these analyses require information regarding such factors as geologic structure (e.g., joint orientation, direction and angle of dip); depth, direction of flow, and slope of the groundwater table; thickness and makeup of the regolith; degree of solution development and present level of activity; relief and topographic expression; size of area being drained by the sinkhole; location of known or assumed points of discharge; precipitation and flood levels; well locations and level fluctuations; location and size of swallets; and potential for further residential or commercial development. As with sinkhole problems in general, problems resulting from their use for drainage fall into two categories: those related to subsidence, or collapse, and those related to flooding. Regardless of which of these problems is being considered, the designer must always be alert to the fact that the treatment being applied to one may result in the development of the other. The success of future preventive and corrective measures will depend on more intensive geological and geotechnical investigations, as well as more stringent land use restrictions and building codes.

Much has been written about the cause and development of sinkholes and the recognition of flood- and collapse-prone sinkhole terrain in relation to highway planning and design, yet very little seems to have been published about their treatment. There are probably several reasons for this, the principal one being that most treatments are viewed as tentative or experimental, and, because scientists and engineers are sometimes reluctant to write about things that are inconclusive or projects that are incomplete, case histories do not get written. A second reason, allied to the first, is that investigations of sinkholes rarely produce absolute and finite data that can be applied in strict quantitative analysis. Treatments, therefore, must be based on experience and judgment and a more or less qualitative analysis and evaluation of whatever information is available. Such a practice, in effect, involves "design without numbers," which runs contrary to the precise analytical methods of most scientists and engineers.

In general, sinkhole problems can be placed in two categories: those related to subsidence, or collapse, and those related to flooding. Regardless of which of these problems is being considered, it must always be kept in mind that the treatment being applied to one problem may result in the development of the other. In other words, the treatment of a collapse problem may produce flooding, and the treatment of a flooding problem may result in subsidence or collapse. It is important, therefore, that the designer be alert to any side effects that might result from a particular design.

Several experiences with both collapse and flooding problems associated with highway design and construction are described.

FACTORS TO BE CONSIDERED

Sinkholes have long been used for drainage in the design of highways. Unfortunately, however, little attention has been paid to the side or long-term effects of such practices, especially in areas of continuing commercial or residential development. Furthermore, decisions to use sinkholes have been based more on expediency than on engineering and scientific analysis, apparently because, as indicated previously, sinkholes are not considered totally analyzable. There are several factors, however, that should be evaluated when traversing sinkhole topography, especially when considering the use of sinkholes for drainage. Among these are