

Geologic Indicators of Catastrophic Collapse in Karst Terrain in Missouri

James H. Williams and Jerry D. Vineyard, Division of Geology and Land Survey, Missouri Department of Natural Resources, Rolla

Although the records of 97 catastrophic collapses in Missouri karst terrain have emphasized such man-made causes as dewatering, vibration, or water saturation, there is an underlying commonality of geologic features that offers insight into ways to avoid collapse problems in highways and other construction. Collapse events are more likely to occur in areas overlain by moderately thick residual soil, in losing valleys, and in wet seasons. Significant collapses have occurred where there was no indication of sinkholes or other typical karst landforms. Of the numerous collapses related to highway construction, most have involved upward stoping of residuum from underlying cavernous channels in carbonate bedrock, and have been triggered by constructional or operational activities that altered drainage conditions. Exploration for incipient collapses is costly and more effective in limited areas. Analysis of geologic indicators such as losing streams, relict karst landforms, and residuum type and thickness, as well as speleological data offer more cost-effective techniques to define target locales for subsequent detailed exploration. Initial exploration with a backhoe generally gives more useful near-surface data than drilling. Drilling is necessary, however, to validate evidence inferred by surface geologic indicators and geophysical methods such as fixed-depth resistivity and high-precision gravity surveys.

Both collapse and subsidence represent vertical settling of the land surface (1), but our interest is directed more to collapse. The unpredictability of collapse and its catastrophic mode of occurrence add a risk factor to all aspects of land use in karst terrain, whereas the gradualness of subsidence permits salvage or the repair of damage.

The records of collapse have emphasized man-related causes such as dewatering, vibration, or water saturation. However, there are a commonality of natural conditions and a history of surface failures involved with most collapse events. In Missouri, of the 97 catastrophic surface failures recorded since the 1930s, 46 can be attributed to some activity of man (Figure 1). Of these, water was a contributing factor to the 52 percent in which leaky utility lines and altered surface drainage conditions attributed to roads and other urban developments had weakened the overburden. Water saturation

by impoundments was a primary cause of 22 percent, while 15 percent were due to dewatering, 7 percent to highway construction, and 4 percent to blasting. Most of the catastrophic failures caused by altered drainage have also involved roads and streets. Thus, road construction and use are directly or indirectly prominent contributors to collapse and subsidence in karst terrain. However, nearly all of these man-related surface failures occurred in regions where natural subsidence and collapse events were common.

Catastrophic failures are as apt to occur in broad, subsiding sinkholes as in karst terrain having closely spaced pinnacles of carbonate bedrock: The soil mechanics properties of the overburden are of more importance than the bedrock configuration in considering the likelihood of collapse versus subsidence. Catastrophic collapse in carbonate terrain can occur where there are no sinkholes. Thus, if one assumes that it will occur only in areas having well-defined sinkholes or broad areas of subsidence, some hazardous areas may be overlooked.

BACKGROUND

Through the years, general features have been given to aid in the identification of areas subject to subsidence and collapse. Foote (2) listed seven conditions that are common in areas of karst topography subject to collapse. He pointed out that there are few sinkholes where the overburden is less than 10 m (33 ft) thick, that the water table is usually below the overburden and the bedrock weathering irregular or pinnacled, and that there are often extensive cavernous openings and major structural elements in the underlying bedrock.

Vineyard and Williams (3) have cited 11 features that may foretell of collapse or subsidence in stream valleys developed in karst terrain. Generally, losing valleys with poorly graded alluvium, angular valley cross sections, and irregular valley gradients are indicative of areas subject to collapse events.

Aley, Williams, and Massello (4) have described seven diagnostic characteristics of karst terrain where catastrophic collapses, primarily those induced by construction of impoundments such as small lakes and sewage

lagoons, but also some caused by changes in ground-water level, have occurred.

FACTORS IN CATASTROPHIC COLLAPSE AND SUBSIDENCE

Records of sinkhole collapse in Missouri are admittedly scanty and incomplete. Our mutual interest in the topic began in the early 1960s and peaked in the spring of 1973, an unusually wet season.

Alterations of soil moisture and groundwater account for most land surface failures in karst terrain in Missouri and elsewhere. The type of failure (subsidence or collapse) is partially related to the intensity and magnitude of the changes. The mechanical properties of the soil overlying the bedrock and the hydrologic characteristics of the region also affect the type of land surface failure. For example, 13 catastrophic collapses occurred in remote timbered areas of Missouri during a 2-month period in the spring of 1973. This was a period of sustained, abnormally high rainfall with precipitation 3 to 6 in higher than normal for those months. These failures were typical catastrophic collapses in karst terrain. The sinkholes were cylindrical, 12 to 18 m (36 to 60 ft) deep, and 6 to 7 m (20 to 25 ft) in diameter (Figure 2). They occurred on uplands and ridges, and in floodplains.

Although collapse or subsidence as a result of highway construction is not a principal cause of surface failure in karst terrain, when such failures occur the results can be serious in both monetary loss and danger to human life. The most notable collapse in Missouri that could be attributed directly to highway construction occurred in February 1966, in Pulaski County (3). While the surface collapse that permitted entry into an active cave system beneath the highway was caused by water discharge on the downstream end of a box culvert, there was an additional active collapse occurring in another part of the cave beneath the shoulder of westbound I-44. This part of the cave, mostly in residual soil, was enlarging upward as chert boulders and soil fragments fell from the roof. Other dome roofs in the cave system were inactive, but this one showed active roof failure; here traffic vibrations could be felt.

The most tragic of such incidents occurred in 1967 in Hannibal, Missouri. Small depressions formed during highway construction through a limestone formation that has a maze of caves had resulted in several small collapses. Three boys entered one of these openings and were never found. Several similar examples have occurred throughout Missouri. Of all the dangers in construction through karst terrain, these small and easily overlooked openings are the most lethal and yet the most subtle.

Such variables as loading, vibration, excavation, and fill changes of the landscape are not the primary causes of subsidence or collapse in highway construction. Rather, the important factors involve a number of minor alterations that culminate in changing the water regimen. The most serious example of the effects of the combination of many minor factors exists in the eastern Missouri Ozarks at Farmington. Here, at least 22 large catastrophic failures have occurred during the past 40 years within an 0.8-km (0.5-mile) radius. The failures have occurred under city streets, buildings, lawns, and in open grounds. These collapses are predominantly in the built-up portion of the city, and their rate has increased during the last 10 to 15 years.

The collapses are vertical-walled sinks, some 6 to 7 m (20 to 25 ft) in diameter and 9 to 12 m (30 to 40 ft) in depth. Dolomite bedrock, which underlies the region, may be exposed as pinnacles, and some water may be

present. Exploration drilling has shown that the bedrock ranges from 3 to 4 m (10 to 20 ft) to more than 22 m (70 ft) beneath the surface. Areas of excessively thick soil cover and sink occurrences have developed along major joint trends. Collapse has been attributed to traffic vibrations, to rainfall, and to the concentrated water sources typical of a city with poor housekeeping procedures.

Mining and mine dewatering have extended to within 2 km (1.5 miles) of Farmington. However, collapses were recorded at least 30 years prior to the mining and have continued for 10 years subsequent to the completion of mining activities. Although deep mines exist in Missouri in areas subject to catastrophic collapse and continuous dewatering is required for mining, only minor surface effects have resulted. In other portions of the United States and in Africa mine dewatering has been a major cause of massive catastrophic collapse (5, 6, 7).

The description of collapses by Aley, Williams, and Massello (4) deals primarily with alteration of the landscape by man, especially changes of groundwater levels or variations in soil moisture. For the most part, these involved water impoundments and sewage lagoons. Some were attributed to drainage alterations caused by construction of early logging railroads.

Vineyard and Williams (8) have described a sinkhole near Lebanon, Missouri, in the western Ozarks as possibly being triggered by the Alaskan earthquake of March 27, 1964. A previously existing sink filled with loess was exposed on one edge of this sink. Recent work (9) has shown that loess of Yarmouth and Sangamon ages filled or partially filled sinks within this area. Thus, the intermittent collapse of sinks for more than 30 000 years emphasizes the persistence of construction problems in karst terrain. At least one catastrophic collapse in paleokarst in Mississippian limestone capped by Pennsylvanian and Pleistocene sediments has been recorded.

REGIONAL CHARACTERISTICS OF KARST SUBJECT TO SUBSIDENCE AND COLLAPSE

As described by Davies and LeGrand (10), karst provinces in the United States are numerous and diverse. Karst develops in bedrock of all ages. It can be found on the plains or in mountains and in rocks ranging from limestone to gypsum. Well-known karst areas include the Appalachians from Pennsylvania to Alabama; Kentucky; Indiana; Tennessee; the Ozarks of Missouri and Arkansas; the plateaus of Texas and eastern New Mexico; and the coastal plain of Florida. The most common cause of subsidence and collapse in these regions is the changing of water regimens.

The most common bedrock type in which karst develops is limestone or dolomite, but collapses have occurred in areas underlain by sandstone, such as those in the St. Peter Sandstone in Warren and Perry Counties, Missouri. Karst phenomena have been reported in many kinds of rock (11). Allen (12) has pointed out that collapse and subsidence can occur in materials ranging from loess to frozen gravel. Spectacular failures have been recorded in places where gypsum deposits are widespread, particularly in areas of Texas and Oklahoma (13, 14).

Although local karst features can be diagnostic in pinpointing areas having a greater likelihood of collapse and subsidence, these indicators may have limited regional usefulness since the various physical properties of karst are the result of local conditions.

Although cavern roof collapse in bedrock has been cited as a cause of catastrophic sinkhole formation (15, 16), no contemporary event that could be attributed directly

to this cause has been observed. While bedrock cavern roof collapse (breakdown) is a normal and regular occurrence in the cycle of cave development, when viewed in the perspective of time such events are rare. When dealing with caves in bedrock, it is more useful to determine the stability of cavern roofs (17) and perform necessary corrective measures.

The downward weathering of bedrock is a more common cause of collapse and subsidence than the upward

mechanical failure of cave roofs. Most collapses have occurred where there is a moderately thick mantle of soil. In Missouri few collapses occur where the soil cover is less than 18 m (60 ft) thick (Figure 3). Collapses are rare where the soil thickness is less than 12 m (40 ft). A thick soil cover provides a setting that accelerates the chemical weathering of bedrock: Soil pH readings range from 4 to 5 in areas of thick soil cover but are near 7 in thin soil areas. Water can be produced

Figure 1. Causes of sinkhole collapse in Missouri, based on partial records gathered since 1930.

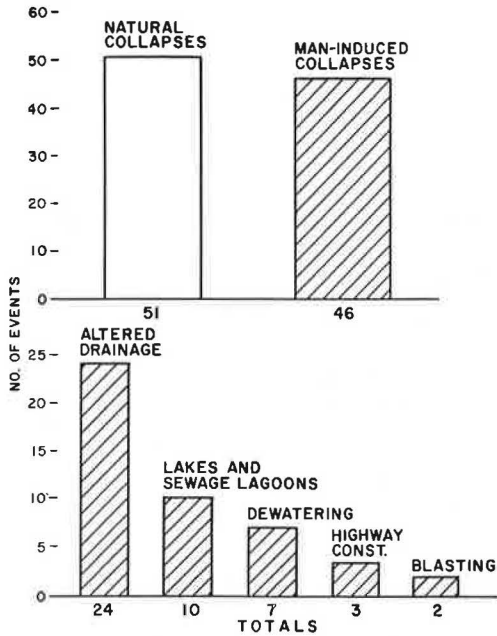


Figure 2. Typical sinkhole collapse common to uplands or valleys in Missouri.

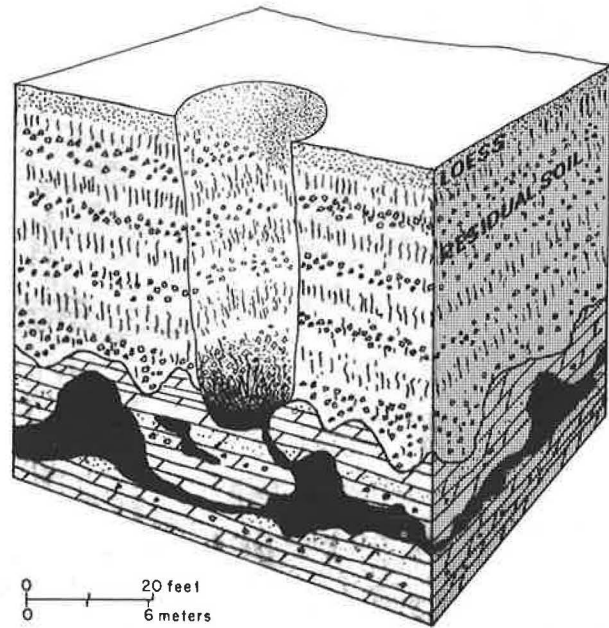
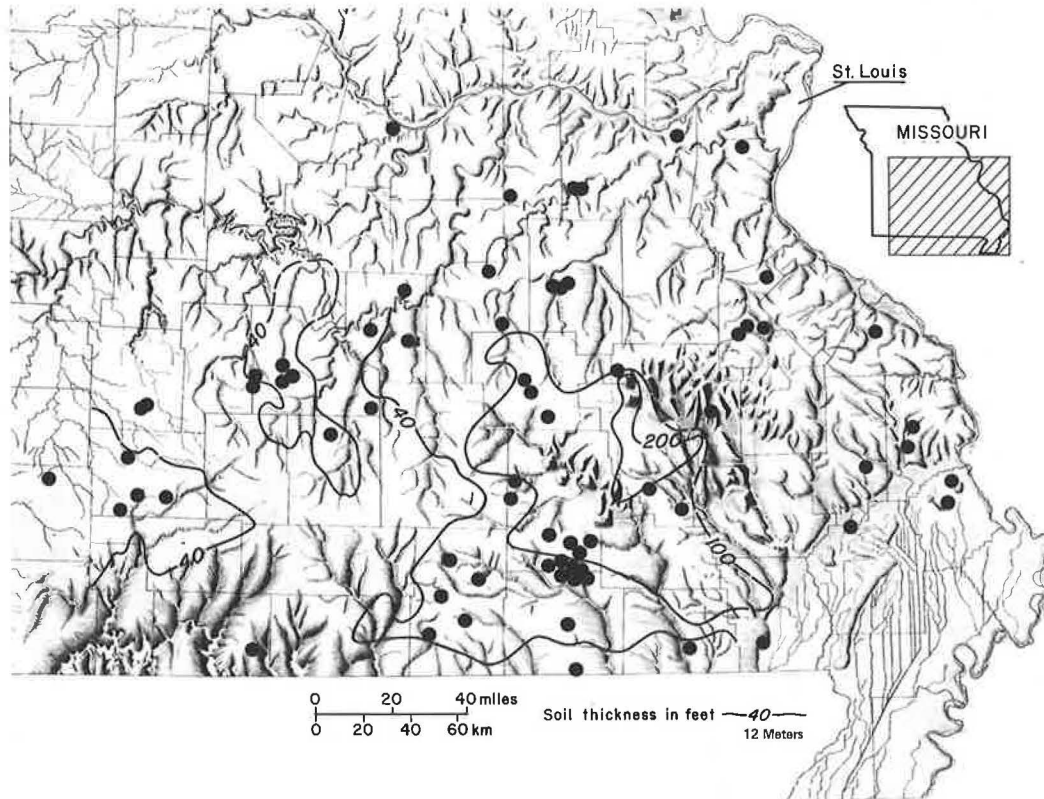


Figure 3. Locations of sinkhole collapses as related to thickness of residual soil.



in minor quantities from wells drilled in thick soil deposits of the Ozarks. Thus, the initial phase leading to collapse is downward, not upward, weathering even though the actual collapse is triggered by mechanical upward stoping.

To understand the mechanics of such events it was necessary to study several sites where catastrophic collapses were imminent. A typical example is at the construction site for a theater at Fort Leonard Wood in the central Missouri Ozarks. Excavations for footings and utility lines were being made at the site, on an upland plateau setting, in soil derived from weathering of the Roubidoux formation, a sandstone, chert, and dolomite sequence. Investigation of a small hole exposed in a backhoe trench showed a vertical shaft 23 m (75 ft) deep, beneath the excavated trench, that was entirely in residual soil. The shaft had developed by gravity stoping from below until the roof was within 2 m (7 ft) of ground level. There was no evidence of sinkholes at the site or in the immediate area. Given favorable conditions of soil moisture, vibration, or other triggering mechanism, a catastrophic collapse would have occurred by the failure of the 2-m (7-ft) residual soil section. The resulting sinkhole would have had vertical sides. There was no access to underlying cave passages through which the soil material had been previously transported. Numerous collapses with the same characteristics (vertical walls in residual soil and the final remains of collapse material blocking access to cavern passages) have shown little evidence of the large volume of material that has been removed. Thus, a long period of time must be involved in the development of conditions that lead to a catastrophic collapse.

As examples of the variations in karst, and indicators of karst-related failures, consider three manifestations in Missouri. Well-defined sinkholes occur in some areas where 3 to 14 m (10 to 45 ft) of transported and residual soil cover slight to moderately weathered limestone and dolomite. In southern Missouri, solution and surface erosion have formed a pattern of coalesced sinks in an area of thick residual soil and deeply weathered bedrock. A third type of karst described as losing watershed terrain has thick residual soil over cavernous bedrock. Losing watersheds and streams are widespread, but few sinkholes exist in this region.

WELL-DEFINED SINKHOLE TERRAIN

Much of the limestone and dolomite countryside in the central, eastern, and southwestern portions of Missouri has karst development expressed as classical, well-defined sinkholes that drain into solution-enlarged cavities developed along joints and bedding planes. Cave passageways, while extensive in length, are not cathedral in size. Consequently, during periods of excess rain, the maximum storage capacity of the subsurface cavities is reached relatively quickly. Surface water flow can then be observed in stream channels flowing across limestone and dolomite terrain pockmarked with sinkholes. Soil cover averages 8 m (25 ft) in thickness.

The only area of well-defined sinkhole terrain in Missouri having a history of catastrophic collapse is in the southwest. Here, the soil cover ranges from 8 to 14 m (25 to 45 ft) in thickness. It is a residual clay having low plasticity (MH; A-7-5), and is characterized by retaining the relict fabric of the parent bedrock, a cherty limestone. The clay minerals have been classified as kaolinite (18), halloysite (19), and dehydrated halloysite (20). The structure of the soil is medium to coarse angular blocky: Individual soil peds have high dry strength and break with a brittle fracture when struck. Although the clay fraction commonly exceeds 60 percent,

the soil is well drained. Macroscopic fractures and the relict bedrock patterns facilitate subsoil seepage (water movement).

The residual soil indicative of an area subject to land surface failure by catastrophic collapse has low in-place dry unit weight [1 to 1.2 g/cm^3 (65 to 75 lb/ft^3)]. While the strength of the individual peds is due to capillary forces and cohesion, the strength of a cave roof in the residual soil is due more to frictional forces between dry fragments of soil and angular chert gravel. Collapse of an upward-stoping dome is preceded by fall of these angular fragments from the roof. Surface failure usually does not occur, even under wetted conditions, until roof thickness is less than 2 m (7 ft). Catastrophic collapses are not common where transported or residual soils having mechanical properties described as CL to CH (A-6 to A-7-6) cover the bedrock.

The most common problems caused by construction are those that involve interference with surface runoff into sinkholes. The changing of spring discharges, usually on property owned by others, is a frequent result of this. Early recognition of these conditions in eastern Missouri prompted the relocation of Interstate 55 so that the highway would lie outside a karst area drained internally by sinkholes.

COALESCED SINKHOLE TERRAIN

A second type of karst development in Missouri is that of a moderately rolling landform of coalesced relict sinkholes, but few active, well-defined sinks. In this type of area preexisting, well-defined sinkholes have been destroyed by subsequent surface erosion and subsurface solution and subsidence. The soil cover averages 18 m (60 ft) in thickness.

The lack of obvious sinkhole development in these areas has led to unfortunate choices of location for several projects. Numerous dry lakes exist in the area. Garbage dumps have been placed in relict sinkholes. Several collapses have been caused by works such as sewage lagoon operation. Although these areas have not had many failures, where failures do occur they are catastrophic rather than gradual.

For the most part, the soil material preserves the fabric of the parent bedrock, a dolomite. It is predominantly a residual clay with properties similar to those previously described. Collapses have occurred on the uplands and in floodplains. Bedrock is exposed in some, but caves also exist entirely in the residual soil.

The most widespread area of karst in Missouri is in the central Ozarks. However, few classic karst landforms are found there. Rather, the region consists of deeply weathered, highly permeable residual soil, underlain by massive cavernous dolomite and dolomite-sandstone bedrock. Some of the larger springs in the United States are here but there are few sinkholes. Nevertheless, this area has had the greatest number of catastrophic sink collapses in Missouri. Some watersheds draining several hundred square kilometers may have flow only once every 2 years. These losing watersheds and streams are a type of landform in which numerous catastrophic failures have occurred. While attempts to delineate points of potential collapse have been unsuccessful, attempts to describe areas of greater likelihood of collapse have been successful. For example, no collapses have been recorded where soil thicknesses are greater than 65 m (200 ft). Collapses more frequently occur where soil thickness ranges from 12 to 30 m (40 to 100 ft).

Catastrophic collapses seldom occur on gaining watersheds or streams. They occur in losing watersheds or streams, and more commonly in the stream valleys of

Figure 4. Typical collapse sinkhole with relict bedrock structure in residuum.



these watersheds. It is rare for a natural collapse to occur where the groundwater level is below the level of the cave passageways in a floodplain.

The collapses are large, at least 6 m (20 ft) in diameter and usually 15 to 18 m (50 to 60 ft) in depth. They are sudden, and nearby residents usually describe the event as a thunderous, ground-shaking occurrence. Some occur only in residual soil, but the larger ones usually involve lower cave passageways in bedrock. Some activity by man is responsible for almost 50 percent of the catastrophic collapses we have documented. Usually, the soil of the sidewalls of the collapse has retained the fabric of the relict bedrock structure (Figure 4).

EXPLORATION PROCEDURES

Surface examination prior to the use of costly or time-consuming investigative tools is an important exploration procedure, as is the recorded history of collapse in local areas. Speleological investigations are becoming an increasingly important part of project site evaluations in Missouri. Data gathered during the past 10 to 20 years in the form of cave descriptions and maps are now sufficient in many areas to give considerable insight into the types and dimensions of subsurface karst features that may be expected. For example, caves in massively bedded cherty Mississippian limestone are prone to develop joint-controlled, vertical shafts in bedrock. Thin roofs of cherty residual soil are hazardous to construction activity, but few large natural collapses have been recorded in this setting. In contrast, caves in massively bedded Cambrian and Ordovician dolomites do not develop as many bedrock shafts, but vertical shafts are formed in the overlying thick mantle of residual soil. These shafts are enlarged upward by stoping, which is accelerated by vertical drainage through the permeable residual soil.

Topographic maps are the most cost-efficient method for initial evaluation of karst terrain. Losing watersheds and streams, sinkholes, and areas with only relict karst features have distinctive landform features. These may

be local in character, but are nonetheless useful.

Close attention should be given to the surface and groundwater conditions of the area. The examination should not be limited to the right-of-way, but should include areas several kilometers distant. Hayes and Vineyard (21) have described procedures used to avoid changing shallow groundwater conditions as the result of US-65 construction near Springfield, Missouri. Undue changes of groundwater in this karst setting would have affected the highway as well as an important spring 5 km (3 miles) to the southeast.

Exploration tools that best reveal the fabric of the soil materials should be used. For example, some 1.3 km (4000 ft) of exploration backhoe trenches were dug in an area of proposed tailings ponds in karst terrain in southwestern Missouri. The local area had a history of collapses resulting from man-induced changes, particularly water impoundments. Backhoe exploration exposed the tops of several caverns that were being formed by upward stoping in the residual soil. Trench exploration should also be considered, particularly for construction projects that cross valleys known to be affected by karst conditions. The void diameter of cave domes that collapse is usually no more than 3 to 4 m (10 to 15 ft). Thus, numerous drillholes would be needed to locate such openings, and backhoe exploration may be less costly and permit a more precise evaluation of in-place soil materials.

Love (22) has found that fixed-depth resistivity traversing is a useful exploration technique to outline buried solution cavities. Shallow refraction seismic or expanding resistivity methods were less successful, due to problems of erratic time arrivals, particularly sudden increases in time of travel. Similar results have been in karst areas subject to collapse. Unfortunately, the data usually are insufficient to locate individual cavities. Refraction seismic data have been used to locate caves in massive dolomite bedrock in the foundation exploration of an Army Engineers dam site in eastern Missouri.

Bates (23), in a thorough study of techniques used for detection of subsurface cavities, concluded that airborne or remote sensing methods and seismic methods have limited possibilities of success. He concluded, however, that various electrical resistivity procedures usually have useful results, although their interpretation has been questioned. He recommends the modified Bristow method of electrical resistivity surveying for subsurface cavity exploration.

Several investigators have discussed the use of microwave radio studies in delineation of buried karst topography. This is based on the relation of soil moisture change to the cavity. Kennedy (24) concluded that detection was possible in most cases.

Gravity surveys (25) have been reported as useful in identification of near-surface cavities at Anchor Reservoir, Wyoming. An investigation using seismic methods at this same location by Godson and Watkins (26) has established that seismic data also provide a useful means of cavity delineation. Recently Omnes (27) has used high-precision gravity surveys to aid in the location of cavities. Applied gravity surveys have also been used.

The variations of soil moisture and groundwater conditions in areas of karst are frequently cited as common features. Thus, it would appear that use of thermal imagery could be an aid in delineation of sinkholes. Coker and others (28) have been successful in predicting a sinkhole collapse along a highway near Bartow, Florida, by this method. However, Harvey and others (29) were unsuccessful in attempting to outline potential collapse sites in a karst terrain of central and southwestern Missouri in this way. These investigators have been successful in locating losing watersheds and geologic fea-

tures that characterize areas subject to collapse. Stohr and West (30) also failed in their efforts to outline sinkholes by the use of thermal infrared imagery. They concluded that imagery was best used as a supplement to stereophoto interpretation rather than as a primary exploration tool. Their test area was in a karst region in the Valley and Ridge province of Virginia. Rinker (31) was able to locate active sinkholes in Puerto Rico with thermal infrared scanning equipment. However, these sinks were creating thermal anomalies by discharge of air from caves.

CONCLUSIONS

Geologic indicators such as we have described can be used to outline areas where sudden failure of the land surface by collapse may occur. However, experience has shown that current exploration techniques used to locate individual potential collapses are not cost-effective over large areas, and can be justified only for high-cost applications such as bridge foundations or buildings. For construction projects involving large areas such as highways, reasonable efforts should be made to reduce drainage modifications of both surface and groundwater regimens, because such changes are a major cause of catastrophic collapse. In some circumstances, even a minor route realignment would avoid an area or watershed subject to collapse events.

While a potentially serious threat to travel safety does exist in karst terrain subject to catastrophic collapse, the likelihood of such occurrences under a highway is rare. Thus, it may be difficult to justify detailed and costly subsurface exploration over large areas. Rather, geologic indicators such as those enumerated below and discussed elsewhere in this paper are more useful and cost-effective for engineering projects involving large areas. These indicators can be used to justify some route realignment and additional expenses in drainage control facilities, and also more detailed subsurface explorations for foundations of costly structures.

1. Collapses are more likely to occur in residual soil ranging in thickness from 12 to 30 m (40 to 100 ft).

2. Collapses are more apt to occur in residual soil retaining the fabric of the parent material; they are uncommon in colluvial deposits or in alluvium deposited by gaining streams.

3. Collapses are more likely to occur where the clay fraction has the low plasticity (MH; A-7-5), common to kaolinitic and halloysitic clays.

4. Collapses are not common in poorly drained surface soils even if this surface soil is underlain by other features typical of collapse indicators.

5. Collapses are more apt to occur in losing streams and watersheds than in gaining ones, and they are as common in the uplands or slopes as in the floodplains.

6. Sinkholes per se are not necessarily indicative of land surface failure by catastrophic collapse.

7. Collapses are more frequent in areas underlain by limestone, dolomite, and gypsum, but have been reported in other types of bedrock.

8. Cave systems developed along the soil-bedrock contact are common in areas having a history of land surface failure by collapse.

9. Cave passageways are periodically or continuously drained by cave streams.

REFERENCES

1. N. P. Prokopovich. Land Subsidence and Population Growth. Proc., 24th International Geological Congress, Montreal, Sec. 13, 1972, pp. 44-54.
2. R. M. Foose. Surface Subsidence and Collapse Caused by Groundwater Withdrawal in Carbonate Rock Areas. Proc., 23rd International Geological Congress, Prague, Vol. 12, 1968, pp. 155-166.
3. J. D. Vineyard and J. H. Williams. A Foundation Problem in Cavernous Dolomite Terrain, Pulaski County, Missouri. Proc., 18th Annual Highway Geology Symposium, Purdue Univ. Engineering Bulletin, Engineering Extracts Series 127, Vol. 51, No. 4, 1967, pp. 49-59.
4. T. J. Aley, J. H. Williams, and J. W. Massello. Groundwater Contamination and Sinkhole Collapse Induced by Leaky Impoundments in Soluble Rock Terrain. Engineering Geology, Series 5, 1972.
5. R. M. Foose. Sinkhole Formation by Groundwater Withdrawal, Far West Rand, South Africa. Science, Vol. 157, No. 3792, 1967, pp. 1048-1054.
6. R. M. Foose. Mine Dewatering and Recharge in Carbonate Rocks Near Hershey, Pennsylvania. Engineering Geology Case Histories, No. 7, 1969, pp. 45-60.
7. W. J. Powell and P. E. LaMoreaux. A Problem of Subsidence in a Limestone Terrain at Columbiana, Alabama. Alabama Geological Survey Circular 56, 1969.
8. J. D. Vineyard and J. H. Williams. A New Sink in Laclede County, Missouri. Missouri Mineral Industry News, Vol. 5, No. 7, 1965, pp. 69-71.
9. D. L. Rath. A Study of Middle to Late Quaternary Sediments in a Karst Trap. MS thesis, Univ. of Missouri-Rolla, 1975.
10. W. E. Davis and H. E. LeGrand. Karst of the United States. In Karst (M. Herak and V. T. Stringfield, eds.), Elsevier, New York, 1972, pp. 467-505.
11. J. Avias and L. Dubertret. Karstic Phenomena in Noncarbonate Rocks. In Hydrogeology of Karstic Terrains (A. Burger and L. Dubertret, eds.), International Association of Hydrogeologists, Series B, No. 3, 1975, pp. 31-40.
12. A. S. Allen. Geologic Settings of Subsidence. In Reviews in Engineering Geology (D. J. Varnes and L. Kiersch, eds.), Vol. 11, 1969, pp. 305-342.
13. G. Brune. Anhydrite and Gypsum Problems in Engineering Geology (abstract). Association of Engineering Geologists, Sacramento, 1964, p. 11.
14. W. E. Jameson and J. B. Schiel. Possible Man-Made Sinkholes at Southard, West-Central Oklahoma: A Case Study in Landscape Modification. Oklahoma Geology Notes, Vol. 35, No. 5, 1975, pp. 187-193.
15. W. E. Davies. Mechanics of Cavern Breakdown. Bulletin of the National Speleological Society, Vol. 13, 1951, pp. 36-43.
16. E. L. White and W. B. White. Processes of Cavern Breakdown. Bulletin of the National Speleological Society, Vol. 31, No. 4, 1969, pp. 83-95.
17. J. D. Landrum. A Foundation Investigation of Cherokee Cave Under I-55, City of St. Louis. Proc., 15th Annual Highway Geology Symposium, Rolla, Mo., 1964, pp. 81-89.
18. A. N. Alcott. Clay Mineralogy and Compaction Characteristics of Residual Clay Soils Used in Earthen Dam Construction in the Ozark Province of Missouri. MS thesis, Univ. of Missouri-Rolla, 1970.
19. W. J. Graham. The Effects of Structure on the Consolidation of Compacted Unsaturated Clay Soils. MS thesis, Univ. of Missouri-Rolla, 1969.
20. J. H. Williams. Classification of Surficial Materials. PhD thesis, Univ. of Missouri-Rolla, 1975.
21. W. C. Hayes and J. D. Vineyard. Environmental Geology in Town and Country. Missouri Geological Survey and Water Resources, Ed. Series 2, 1969.
22. C. L. Love. A Geophysical Study of a Highway Problem in Limestone Terrain. Materials and Research Department, California Division of Highways,

- Sacramento, Research Rept. M.R. 642730.
23. E. R. Bates. Detection of Subsurface Cavities. Soils and Pavement Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1973.
 24. J. M. Kennedy. A Microwave Radiometric Study of Buried Karst Topography. Bulletin of the American Geological Society, Vol. 79, 1968, pp. 735-742.
 25. G. P. Eaton. Extended Gravity Survey of Near-Surface Cavities in the Anchor Reservoir, Wyoming (abstract). Association of Engineering Geologists, Anaheim, California, 1968.
 26. R. H. Godson and J. S. Watkins. Seismic Resonance Investigation of a Near-Surface Cavity in Anchor Reservoir, Wyoming. Bulletin of the Association of Engineering Geologists, Vol. 5, No. 1, 1968, pp. 27-36.
 27. G. Omnes. Microgravity and Its Applications to Civil Engineering. TRB, Transportation Research Record 581, 1975, pp. 42-51.
 28. A. E. Coker, R. Marshall, and N. S. Thomson. Application of Computer-Processed Multispectral Data to the Discrimination of Land Collapse (Sink-hole) Prone Areas in Florida. Proc., 6th International Symposium, Remote Sensing of the Environment, Willow Run Laboratory, Univ. of Michigan, Ann Arbor, 1969.
 29. E. J. Harvey, J. H. Williams, and T. Denkel. Role of Remote Sensing in Studies of Groundwater-Surface Water Relationships in Missouri. U.S. Geological Survey (in press).
 30. C. J. Stohr and T. R. West. Delineation of Sink-holes Using Thermal Infrared Imagery. Laboratory for Application of Remote Sensing, Purdue Univ., West Lafayette, Ind., 1974.
 31. J. N. Rinker. Airborne Infrared Thermal Detection of Caves and Cave Crevasses. Photogrammetric Engineering, Vol. 41, No. 11, 1975, pp. 1391-1400.