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Characteristics of Sinkhole Development and Implications for Potential Cavity Collapse

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ABSTRACT

The results of investigations conducted in the karstic coastal plain of Florida indicate that the potential for cavity collapse is significantly greater in topographic lows where existing sinkholes, depressions, and other surficial features are lineated. Fracture traces and these lineaments can be established by interpretation of aerial photographs. In one case study it was found that almost all recent sinkholes occurred in the vicinity of the intersection of lineaments. A high vertical permeability to promote solution of carbonates and to induce piping of overburdened soils seems typical of many cavity and sinkhole systems. Collapse of overburden into cavities generally appears to be triggered by depression of the water table followed by wet surface conditions (e.g., well pumping and irrigation). Details of these investigations are presented with some emphasis on the lack of definitive geophysical and remote sensing methods for cavity detection. Several examples are presented to illustrate the difficulty in detecting subsurface cavities in conventional foundation investigations and in the analysis of the in situ conditions triggering the collapse. The subsidence of a portion of Interstate highway is discussed in relation to the observed in situ conditions.

Sinkholes and karst terrain are generally associated with the solution of limestone or, to a lesser degree, dolomite in regions with at least moderate rainfall. Arid or semiarid regions normally do not exhibit significant karst development, although any solution features observed in these dry regions are probably remnants from periods of more humid climatic conditions (1).

Nearly 15 percent of the contiguous United States has soluble rock at or near the surface (2). Puerto Rico is noted for its extensive solution features, particularly its pepinos. Gypsum beds in Canada provide a spectacular example of sinkholes. Even in the high velt near Johannesburg, South Africa, solution of dolomite rock occurs although the average annual rainfall is only about 35 in.

Karst terrain exists in many locations throughout the world, but it does not seem to have an extensive effect on highway alignment, site selection, foundation investigations, or performance of structures. Concern about the hazards associated with cavity collapse is mainly evident when a dramatic failure or a substantial economic loss occurs--for example, the Winter Park, Florida, sinkhole in 1981.

Sinkholes are continually developing in the more active regions of Florida. Many of these go undetected because they occur in sparsely developed regions. However, the probability of structural damage caused by cavity collapse will most likely increase as development and urbanization become more intensive.

There are numerous factors that influence the solution process and the development of subsurface cavities. It is essential that the soluble rock have a reasonable degree of water flow. This means that the rock must have adequate permeability and flow of water to allow replacement of water saturated with dissolved ions with less saturated water. Permeability has been characterized as either primary porosity (intergranular) or secondary porosity (fractures and joints) (3).

Primary porosity is dependent on interparticulate openings in the rock, shell beds, or coquina deposits. Numerous small solution pits may form because of downward flow of water in deposits located above the water table. Horizontal flow below the water table can produce small caves or irregular conduits (3).

Secondary porosity refers to flow along cracks, joints, and discontinuities that are generally caused by tectonic movements and stress release in the rock. Highly fractured zones in carbonate rocks yield greater quantities of water than nonfractured zones (4-6). Flow is often much greater than through interparticulate openings. Consequently, the rate of solution may be significantly greater, especially as the cracks, joints, and fracture zones become enlarged and the water flow rate increases. Water flow along bedding planes is also categorized as secondary porosity.

Local or regional variations in topography and stratigraphy also have a definite effect on water availability and flow through soluble formations. Slightly higher terrain elevations with slopes adequate to promote surface runoff and to minimize water retention have a tendency to reduce solution activity. Similarly, low permeability layers, such as clays, effectively reduce the downward flow of water but may concentrate water at discontinuities in the stratigraphy that can produce accelerated solution and sinkhole development. Terrains with perched water tables are usually not candidates for sinkholes except in zones of discontinuities where horizontal flow and secondary porosity are high.

Climatic variations and pumping from wells in shallow and deep aquifers can conceivably increase water flow and solution activity. This may be a long-term effect, but it is also important from the standpoint of increasing the potential for inducing roof collapse or raveling of existing solution cavities.

Variation in water table may also be attributed to the presence of cavities and conduits that provide a high downward permeability. There is evidence to suggest that the water table is often depressed in the vicinity of cavities. Observations of existing sinkholes provide a rationale for this: Sediment and debris washed into the throat of the sinkhole often provide a seal that allows water to accumulate until sufficient hydraulic pressure results in a piping failure that drains the pond. Some sinkholes undergo this process repeatedly. After the pond empties, the shallow water table is depressed in the zone surrounding the sinkhole. Other factors influencing cavity development and collapse are discussed in subsequent sections of this paper.

The detection of cavities in rock and overburden is usually a difficult task. Geophysical and aerial remote sensing methods are not always reliable because of in situ conditions and operational limitations of remote sensing equipment. Considerable emphasis has been placed on using resistivity and seismic (e.g., wave-front analysis) techniques. The results obtained using these geophysical methods have been quite variable; the investigation reported by Love (7) is a good example. Anomalies on thermal infrared imagery have been used to identify subsurface cavities, but air temperatures, wind, density of vegetation, and other adverse factors can affect the reliability of this technique.

The investigations presented in this paper were directed toward the use of aerial photography for identification of fracture traces and lineaments and their relationship to the formation of sinkholes. The results of these investigations suggest that the intersections of lineaments constitute potentially high-risk areas for cavity collapse. This is a subjective technique that depends on stratigraphy and local conditions. It is not intended as a method to pinpoint the exact location, size, or depth of a cavity.

CAVITY AND SINKHOLE CHARACTERISTICS

In general, the relationship between the size of sinkholes and the cavity is unknown before collapse. The size of observed sinkholes ranges from about 1 ft to more than 300 ft (0.3 to 91 m) in diameter and 150 ft (69 m) or more in depth. A study conducted in Alabama indicated that the average sinkhole is about 10 ft (3 m) wide, 12 ft (3.7 m) long, and 8 ft (2.4 m) deep (8). Sinkholes that develop in Florida are comparable although it is not unusual to have larger ones that fall in the 20- to 30-ft (6- to 10-m) diameter class.

Figure 1 shows a sinkhole that occurred in the parking lot of the Maracaibo Apartments in Gainesville, Florida, in 1982. Unfortunately, a new 1982 Oldsmobile parked directly over the cavity was buried in the throat of the sinkhole when the collapse occurred. The sinkhole and a portion of the parking lot were located in a lineated depression that was only several feet lower than the surrounding relatively flat terrain.

A recent investigation on Interstate 75 near Alachua just north of Gainesville, Florida, revealed a small cavity in the median at a depth of 45 ft (14 m) that extended to 67 ft (20 m). Borings were 5 ft (1.5 m) on center and only two borings encountered the cavity. Only 5.5 yd^3 (4.2 m^3) of grout were required to fill the cavity. Obviously, on the basis of the amount of grout and the spacing of bore holes, the cavity was narrow and lineated.

Adjacent to this small cavity was a zone of major

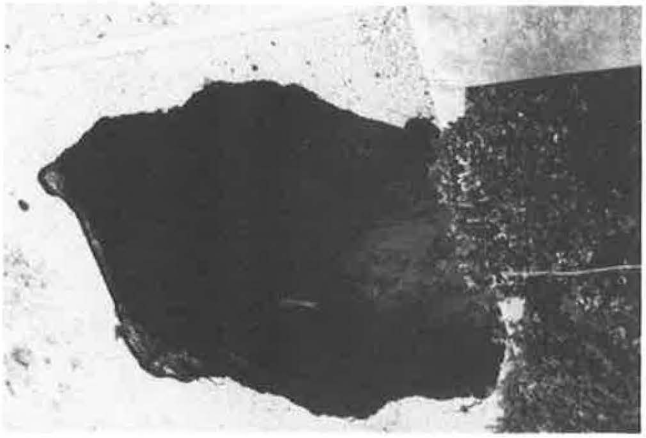

FIGURE 1 Sinkhole in parking lot at the Maracaibo Apartments, Gainesville, Florida.

FIGURE 2 Subsidence on I-75 near Alachua, Florida.

subsidence that was located in a topographic low. The southbound lanes of I-75 were closed because of concern about the possibility of a collapse after a depression and cracking occurred in the pavement (Figure 2).

The distressed area extended from the western portion of the median, west across the pavement, and about 30 ft (9 m) beyond the right-of-way to surface cracks, which were displaced vertically about 5 in. The observed cracks did not form a continuous circular shape but, when mapped (as shown in Figure 3), they revealed an elliptical pattern approximately 140 ft (43 m) wide that was estimated to be more than 180 ft (55 m) long. Borings down to 75 ft (23 m) indicated sandy soils with isolated clayey soil lenses. The water table was not encountered at this depth, even though there had been considerable rainfall for several months preceding the subsidence.

Soft gray limerock was encountered as shallow as 33 ft (10 m) and as deep as 46 ft (14 m) in the median. There were several exceptions where borings terminated at 76 ft (23 m) and 101 ft (31 m) showed sands exclusively. To the west the depth to rock generally increased to 66 ft (20 m) or more. One boring taken in the lowest area southwest of and outside the failure boundary indicated rock at 149 ft (45 m). The surface features, subsurface soils, and depth to bedrock indicated that portions of the subsidence area are located over a narrow solution valley or fracture zone that has been filled with sands and stratified lenses of clay.

Investigations are currently being conducted using resistivity, ground-penetrating radar, and a cone penetrometer in an attempt to identify the source of the problem. However, it is hypothesized that it is a deep-seated failure, induced by localized piping into a cavity, which resulted in the overstressing of overlying soils.

The foundation investigation performed for construction of the Chemical Engineering Building at the University of Florida missed a cavernous cavity system. During excavation of the elevator shaft, a void, which led to the discovery of the cavity, was encountered. A spelunker mapped the cavity (Figure 4). The potential for missing small or narrow lineated cavities with borings for foundation investigations is greater than one might expect.

Sinkholes are usually formed by the collapse of

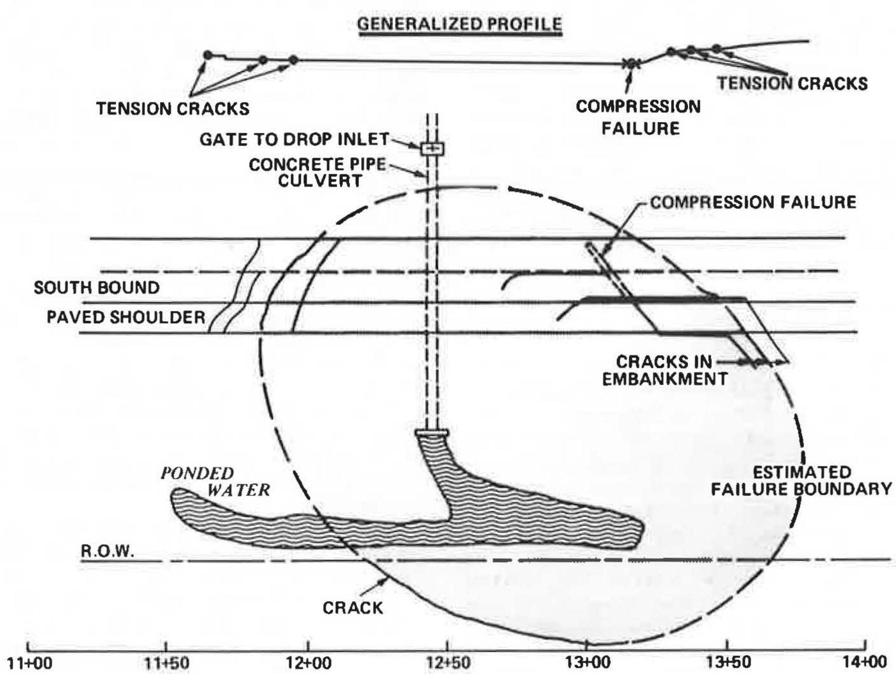

FIGURE 3 Subsidence on I-75 (MP 396.2).

CHEMICAL ENGINEERING BUILDING

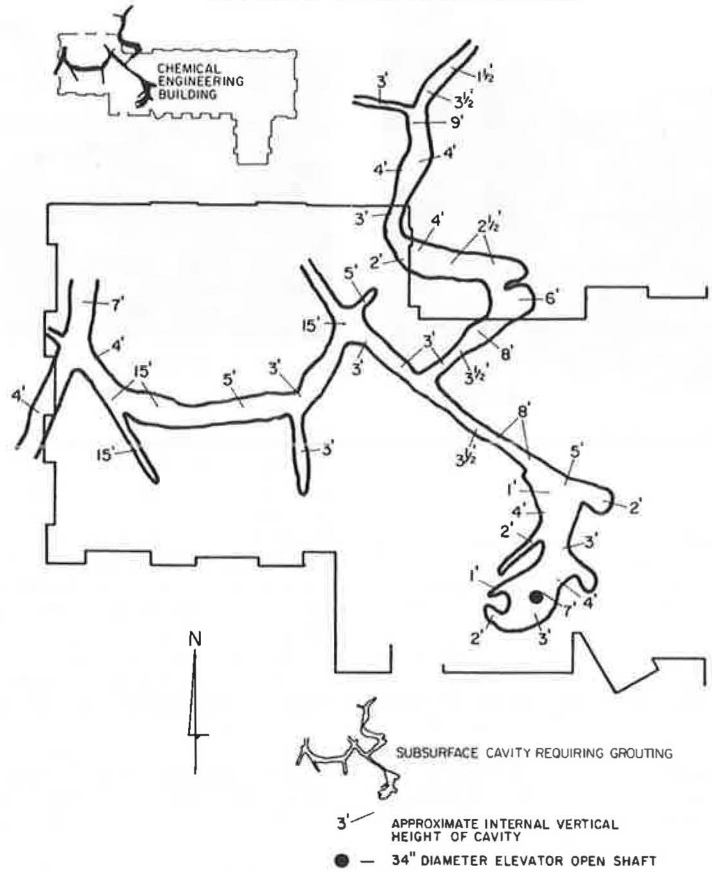

FIGURE 4 Subsurface cavity encountered during excavation of elevator shaft.

rock roofs or by raveling of unconsolidated overburden into an existing cavity (9). Sinkholes often enlarge shortly after initial collapse as a result of localized slope failures or raveling or both. Small vertical sinkholes [e.g., 15 ft (4.6 m) or less in diameter] may retain their initial shape, because of arching action, unless raveling of the vertical faces is pronounced.

The detection of cavities, particularly small ones, is generally not possible unless extensive effort is expended in a subsurface exploration program. However, there are indicators that assist in the pinpointing of hazardous zones and thereby confine subsurface exploration investigations to smaller, more well-defined areas.

REMOTE SENSING INVESTIGATIONS

Land satellite (LANDSAT) imagery and aerial photography have been used to investigate the reliability of using lineaments (photolinears) to identify the most probable locations for sinkhole occurrence. Aligned depressions or dolines and their intersections indicate more active areas that have a greater potential for cavity collapse. Satellite imagery is valuable for interpretation of major depositional and structural features. However, because of its limited resolution, it is not as useful for doline mapping as is high-quality aerial photography.

The identification and mapping of depressions, old sinkholes, and other features from aerial photography is relatively easy except where features are masked by dense vegetation. An investigation conducted near Pierson, Florida, provides a comparison of LANDSAT, high-altitude color infrared, and low-altitude aerial photography (10). The study area is located in the Crescent City-Deland Ridge Section of the Central Lake District. The area is typified by sand hills with summits generally 80 to 100 ft (24 to 30 m) in elevation. Pliopleistocene sand and shell rest directly on the Florida Aquifer (11). Although limited in scope, the study indicated that the intersection of lineaments corresponded to de- pressed zones that contained one or more sinkholes.

Another site near Dover, west of Plant City, Florida, was selected for investigation. During a period of subfreezing temperatures in January 1977, strawberry farmers began pumping from wells to protect their crops from frost damage. The drawdown in an observation well reached almost 10 ft (3 m) in about 4 days, but drawdown in other wells was reported to be 60 ft (18 m). The potentiometric elevations at the observation well of the Riverview Weather Station compared with air temperatures are shown in Figure 5. Numerous sinkholes were reported to have developed in strawberry fields and citrus groves. Twenty-two sinkholes were documented by Hall and Metcalfe (12).

This area lies physiographically in the Hillsborough Valley of the Ocala Uplift District. It is described by Brooks (11) as having sluggish surface drainage and many karst features in a valley from which much of the surficial clastic sediments have been removed. The stratigraphy consists of 10 to 20 ft (3 to 6 m) of surficial sands and 20 to 50 ft (6 to 15 m) of clayey sands, phosphoritic sand and

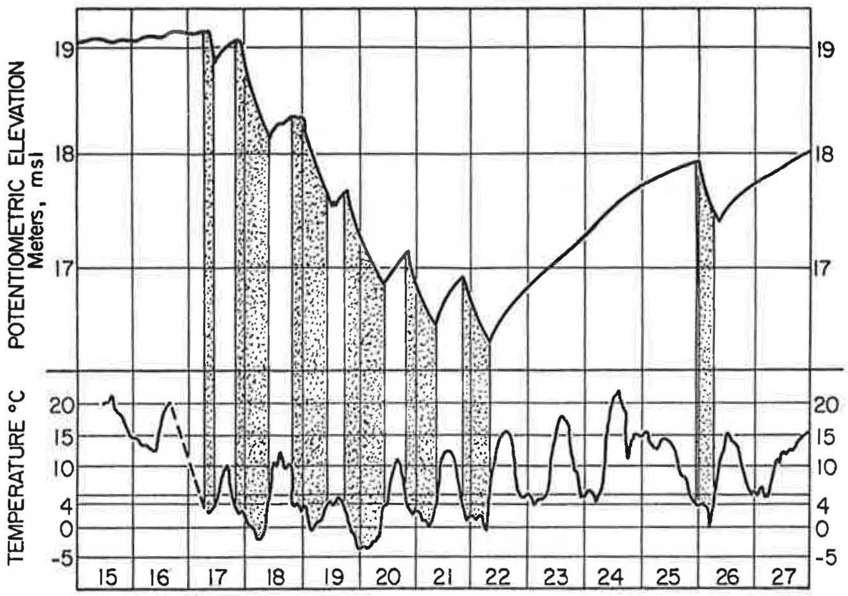

FIGURE 5 Comparison of hydrograph from proposed Thonotosassa well field and thermography from Riverview weather station, Jan. 1977 [after Hall and Metcalfe *(12)*].

gravels, and clayey limestones and dolomities of the Miocene Hawthorne formation underlain by limestone.

Various types of imagery were studied, but Agricultural Soil Conservation Service (ASCS) photographs were used to develop lineament in the study area. The ASCS photographs selected for interpretation were INDEX ASCS-2-68DC Item 5, 1-21-68, BQF-4JJ 32-37, 84-89, and 153-159.

The lineaments were mapped primarily from soil and vegetation tonal alignments, and the linears formed by a few old sinkholes. The lineaments were transferred to a base map that identified the location of the 22 sinkholes. Figure 6 shows this map that illustrates the location of wells, strawberry fields, and new sinkholes in relation to lineaments.

These lineaments are similar to the northeast and northwest trends mapped by Vernon (13) in 1951. The majority of the sinkholes occurs at or near the intersection of lineaments and in slightly lower or depressed areas of the terrain (14). The area south of FL-574 had the greatest activity (17 sinkholes), which is probably attributable to greater drawdown and intensity of overhead irrigation for freeze protection of crops.

Cavity collapses that occurred during construction of the runway for the new Southwest Regional Airport in Lee County provided an opportunity to evaluate photolinears (lineaments) in a different geologic setting. The runway is bisected by a scarp at 25 ft (7.6 m) elevation, which delineates the

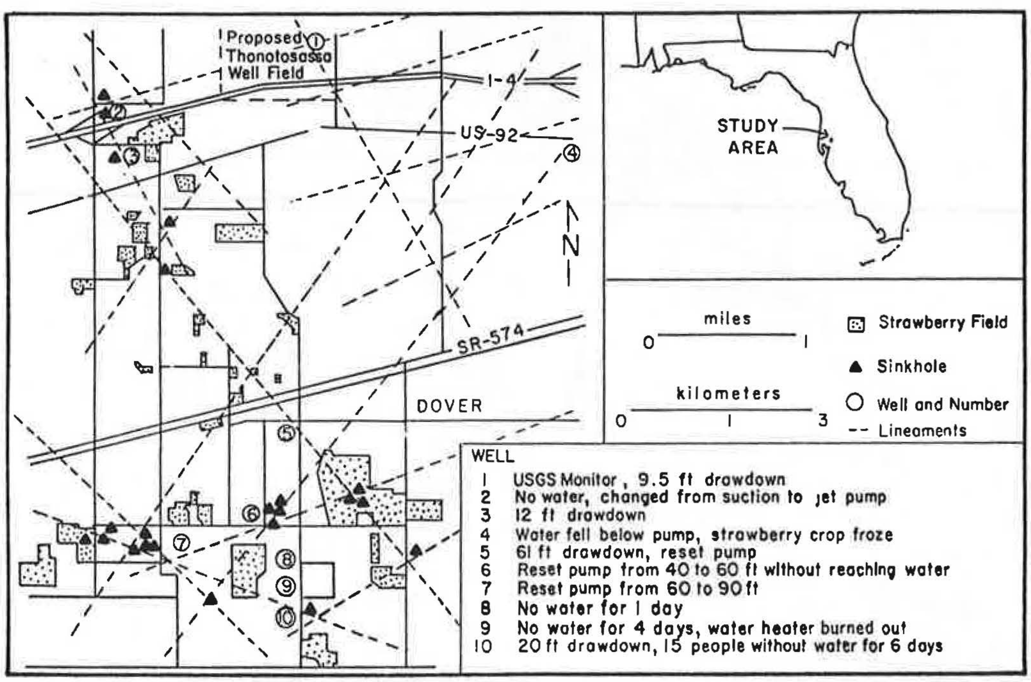

FIGURE 6 Lineament and sinkhole map for study area west of Plant City, Florida [modified from Hall and Metcalfe *(12)*].

boundary between two physiographic provinces, the Immokalee Rise to the east and the Southwestern Slope to the west (15,16).

The Immokalee Rise is characterized as a broad area of land slightly higher than that surrounding it, and typically 30 to 40 ft (9 to 12 m) in elevation above mean sea level (11). This area consists of flatwoods with some wet prairie and cypress swamp. Soils consist of fine sands, and sandy loam and clay, with numerous pockets of shell sands and muck. Permeability of the sandy clay is about one-tenth of that occurring in the fine sands (6 to 20 in./m). The depth of unconsolidated soils (about 20 ft or 6 m) is relatively thin. Water table levels between wet and dry seasons fluctuate about 2 to 15 ft (0.6 to 4.6 m) below the land surface.

LANDSAT, false color composite, high-altitude color infrared, and Florida Department of Transportation black-and-white panchromatic aerial photographs (March 1979) at a nominal scale of 1:24,000 were used for interpretation of regional and local terrain features (17). Interpreted photolinears were

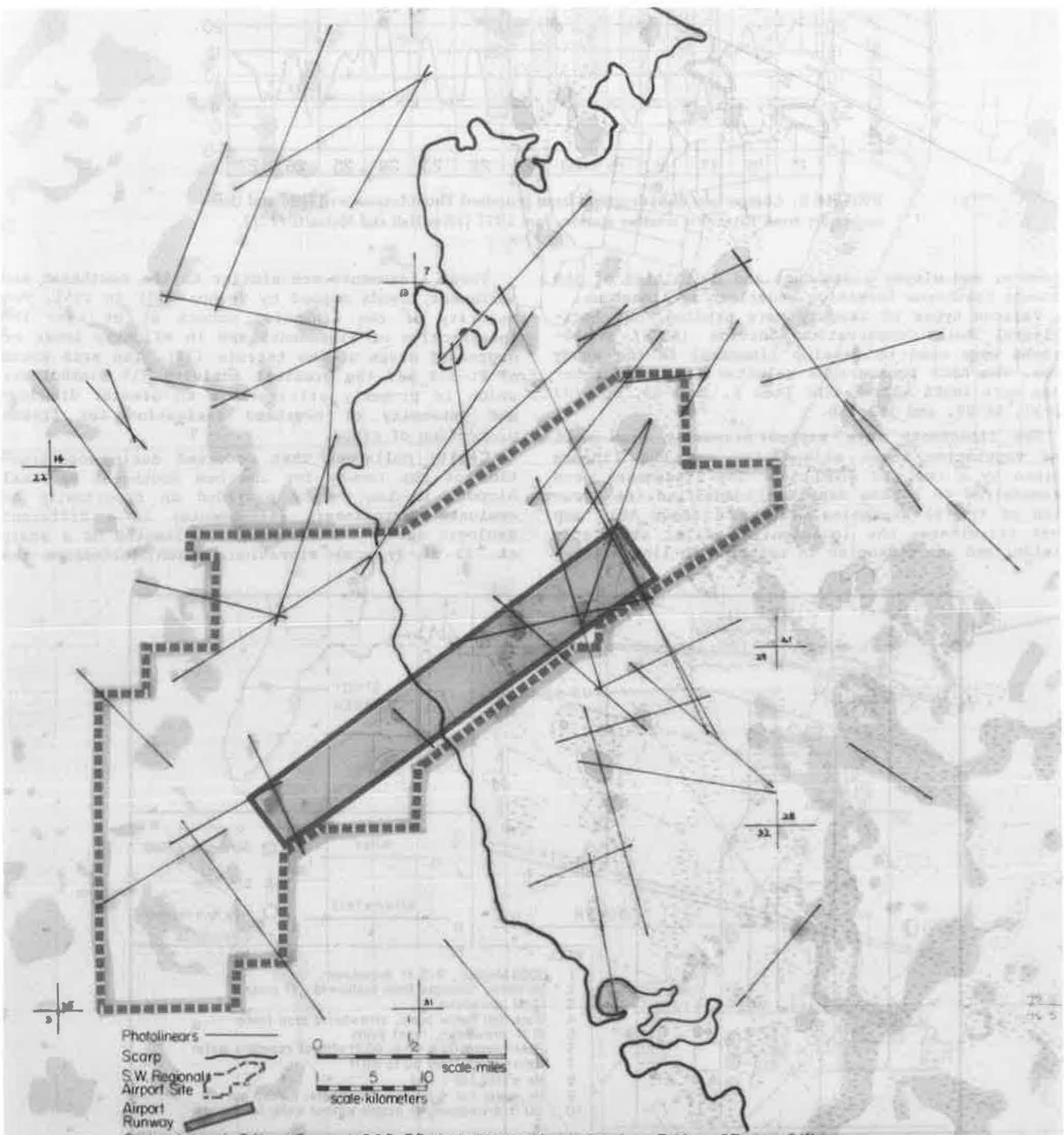

FIGURE 7 Photolinear map of the Southwest Regional Airport site and vicinity, Lee County, Florida.

transferred to a U.S. Geological Survey 7.5-min topographic quadrangle map. Figure 7 shows that the northeastern portion of the airport runway is located in a zone of the Immokalee Rise that has a predominance of photolinears and intersections of these linears. It was also obvious that numerous depressions and wet, swampy areas are located within this zone.

The potential for subsurface cavities and sinkhole development, based on the mapped photolinears, was interpreted as high in the northeastern segment of the runway and relatively low in the southwestern portion. These results correlated well with the sinkholes that had developed during construction. Information about the exact location of these sinkholes was not available, so a direct correlation to photolinear intersections was not attempted.

SUMMARY

Recent subsidence and collapse features in the karstic coastal plains of Florida are generally found in association with old sinkholes and depressions in topographic positions that are low relative to the surrounding areas. Overburden often consists of either permeable soils or more impermeable soils with localized zones of high vertical permeability.

Subsurface cavities and smaller solution channels may provide an excellent conduit for localized removal of surface water and groundwater, depending on the stratigraphy and availability of water from the surrounding area. It has been observed that the water table is often depressed in the vicinity of cavities. This is, to a degree, substantiated by the response of old sinkholes that repeatedly fill until washed-in sediment plugging the hydraulic connection is removed (e.g., by piping). This empties the pond and depresses the shallow water table.

The frequency of sinkhole occurrence has generally been associated with the depression of potentiometric levels resulting from drought or removal of groundwater by pumping of wells. Previously submerged soils overlying subsurface cavities are subjected to an increase in stress because the soil is no longer in a buoyant condition. Noncohesive soils may have a tendency to ravel or spall, eventually failing by collapse or through the continued erosion of soil. The latter case lends itself to hourglass erosion and the formation of a more conically shaped sinkhole.

Cavity collapse seems equally dependent on the availability of surface water to increase the weight of the overburden and, consequently, stresses in the dome of the cavity. The potential for piping to weaken the system is equally high, particularly where sufficient permeability exists or small conduits have been formed. Rainfall and irrigation water that flow on the surface or migrate in the permeable shallow subsurface soils toward topographic lows containing cavities appear to be a major factor in triggering collapses.

The low probability of locating cavities during conventional foundation investigations suggests that more emphasis should be placed on the use of suitable geophysical and remote sensing methods. In situ conditions such as depth to water table, very dry soils, major irregularities in the soil-rock contact surface, and depth and size of cavity influence the selection and use of these methods. Furthermore, it is imperative to have at least some knowledge of the stratigraphy, soils, and geologic conditions before conducting any subsurface exploration program.

Foundation investigations can best be planned using information derived from remote sensing methods that is supplemented by available hydrologic and geologic maps and literature, particularly when alternate sites are being evaluated. Interpretation of low- to medium-altitude aerial photographs for analysis of terrain is essential for identifying surficial and certain subsurface anomalies that affect the location and type of exploration equipment used to evaluate foundation conditions.

The results of investigations in Florida's karst terrain suggest that fracture traces and other photolinears (dolines) are good indicators of the most active solution conditions. The risk of cavity collapse or encountering a cavity along these linears, particularly at the intersection of a photolinear, is quite high. Other investigators have demonstrated that these intersections also provide greater permeability and well productivity.

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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-