Foundation Design in Florida Karst

by John E. Garlanger

The entire Florida peninsula is underlain by solution-weathered limestone, with cavities in some areas that are known to exceed 100 ft (30 m) in height and width. The lengths of these natural conduits are measured in miles. The sinkhole-dotted surface of the limestone is typically buried beneath significant thicknesses of overlying sediment, and the foundation hazards associated with building on the limestone generally are not visible from ground level.

Fig. 1 is a generalized cross section through a hypothetical site in the sinkhole-prone area of central Florida. The limestone is overlain by consolidated clays of Miocene age and unconsolidated sands of Pleistocene age. The groundwater table in the sand is typically within 5 to 10 ft (1.5 to 3 m) of the ground surface and the piezometric level in the underlying limestone is typically 40 to 80 ft (12 to 24 m) below ground surface. Of primary importance from a foundation engineering perspective is the sand-filled breach in the clay layer. Groundwater from the surficial aquifer flows through this breach and recharges the much more productive limestone aquifer.

From a hydrological perspective, this ability to recharge the lower aquifer, which is the principal source of potable, agricultural, and industrial water in central Florida, with water from the rain-recharged surficial aquifer is quite beneficial. However, as the water supply de-

mand in the deeper aquifer causes increases in the hydraulic head difference between the two aquifers, the potential for "piping" sand through the breach in the clay layer into an underlying cavity increases.

Piping occurs when a subterranean conduit or tunnel is eroded backward from a location where groundwater is discharging from an unconsolidated soil deposit, such as at a spring.[1] Once erosion begins, it proceeds backward along the line of maximum hydraulic gradient toward the source of seepage. The end result can be catastrophic for a building foundation.

In Fig. 2, sufficient sand has piped into the cavity system in the limestone to create a cavity in the overburden sands. When the cavity enlarges to a size at which the beam action of the overlying soil can no longer support itself, the roof collapses, resulting in a sinkhole at the ground surface (Fig. 3). Fig. 4 illustrates this phenomenon at a site in the Orlando metropolitan area.

In Fig. 5, the groundwater table is higher, the soil above the water table is cohesionless, and the available void space in the limestone is small. In this case, the depression at ground surface is more saucer-shaped and the subsidence is more gradual. However, because of the resulting settlement, a building foundation constructed above the depression would still have failed. Fig. 6 illustrates this phenomenon at a site near Brooksville, Florida.

If the cavity system in the limestone is large enough or the flow in

the limestone is great enough to carry the eroded material away, the size of the sinkhole is limited only by the thickness and stable slope angle of the overburden (Fig. 7). Fig. 8 illustrates this phenomenon at a site in Winter Park, Florida. The sinkhole shown is over 350 ft (107 m) in diameter and is the largest sinkhole to have occurred in Florida during recorded history.

Site investigations in sinkhole-prone areas

The first step in designing a building foundation in central Florida is to locate the building away from the influence of potential sinkholes. This requires investigating a proposed building site to locate any breaches in the confining layer.

Typically, investigating sinkhole potential begins with studying the regional geology and hydrogeology and mapping historical sinkholes that have occurred in the project vicinity.

Fig. 9, which shows the occurrence of historic sinkholes in Polk County, Florida, was prepared in the early 1970s using data obtained from the Polk County Civil Defense Agency, conversations with local geologists, interviews of private individuals, and a search of newspaper articles. Since 1983, the Florida Sinkhole Research Institute at the University of Central Florida has been accumulating data on historic sinkholes for the entire state. This computerized data base has made it much easier to obtain information on historic sinkholes in
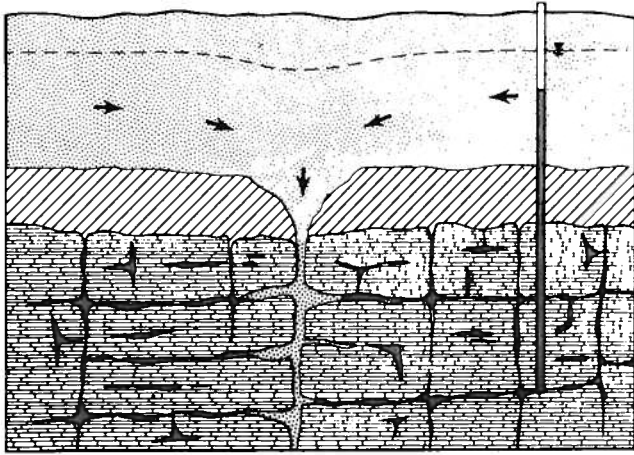
Fig. 1 — Generalized stratigraphic profile for sinkhole-prone areas in central Florida.
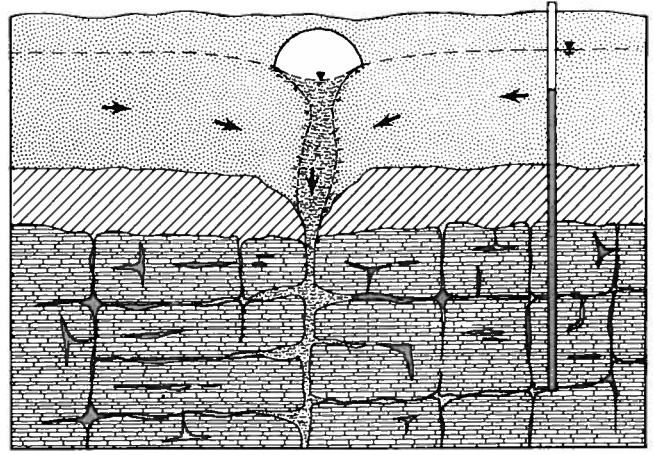

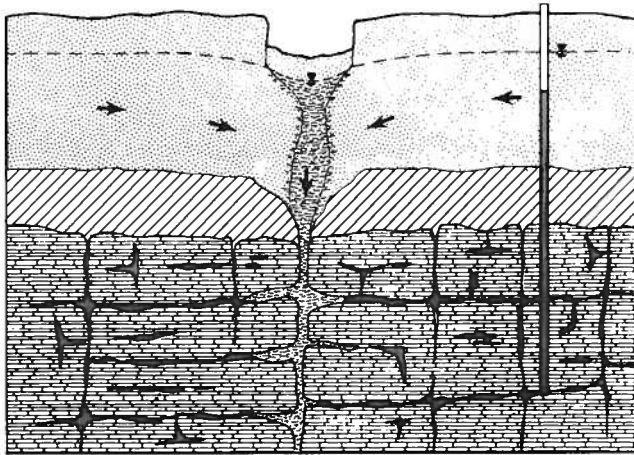Fig. 2 — Early stage in the development of a cover collapse sink.

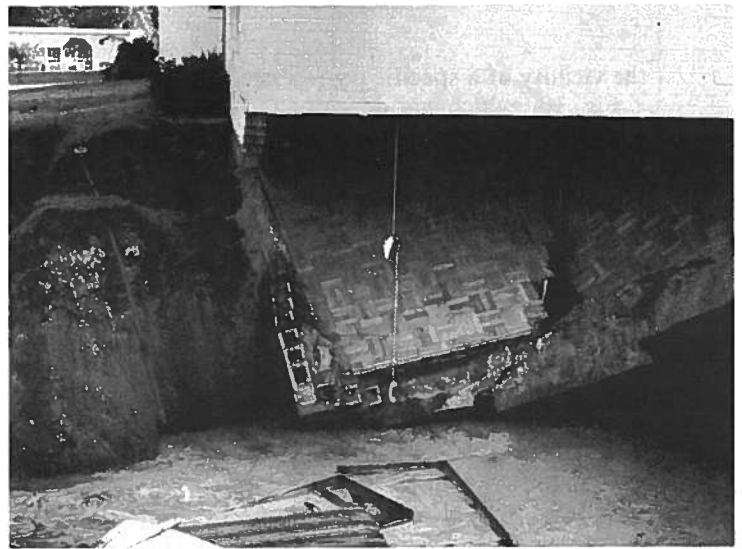Fig. 3 — Final stage, cover collapse sink development.

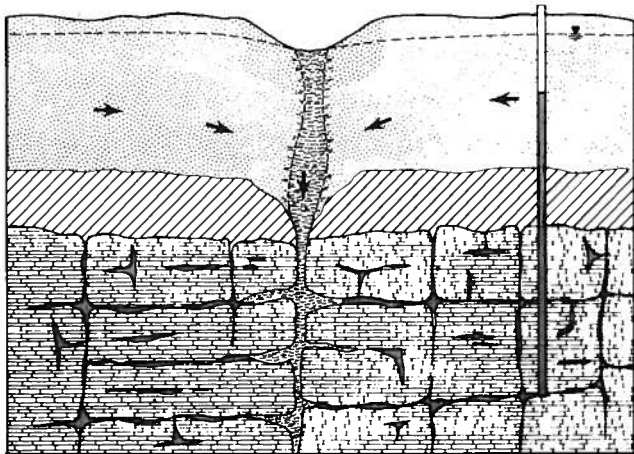Fig. 4 — Cover collapse sink in metropolitan Orlando.

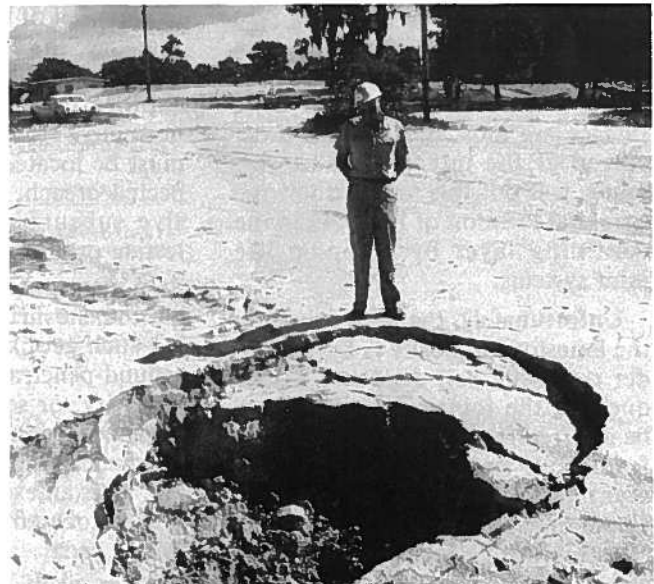Fig. 5 — Development of subsidence sink.

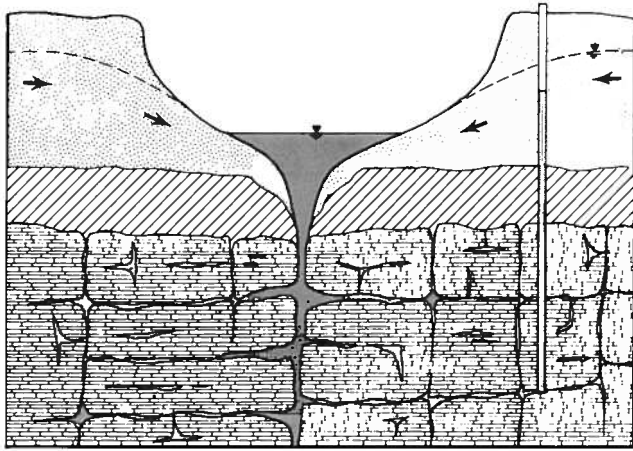Fig. 6 — Overburden subsidence sink near Brooksville.

Fig. 7 — Development of ultimate overburden subsidence sink.

Fig. 8 — Overburden subsidence sinkhole, Winter Park.

the vicinity of a specific project site.

Fig. 10,[2] which was developed using the computerized data base, presents a moving average analysis of modern sinkholes for a 790-square-mile (1270 km²) region in Hillsborough County, Florida. The moving averages were based on a 4-square-mile (6.4 km²) quadrant with a 0.1-mile (0.16-km) step. This map indicates a highly localized distribution of modern sinkholes. The number of sinkholes ranged from 0 to 5 per square mile (1.6 km²) for the period of record. This corresponds to a frequency of sinkhole occurrence ranging from 0 to 0.2 per square mile per year.

Data from historic sinkhole mapping can also be used to locate areas on a proposed building site where a breach in the confining layer is more likely to exist. Because sinkholes in the limestone surface are most likely to have occurred at the intersection of two joints, it is possible to determine the potential location of breaches in the confining layer by mapping the joint systems.

Unfortunately, the joint system in the limestone typically is buried under overlying soil deposits; consequently, the joint system can only be inferred from such linear surface features as stream segments, alignment of lakes, and ponds, etc. These linear or near linear surface features are referred to as lineaments. Fig. 11 is a partial lineament map of south Orlando. Note that

there are two sets of lineaments, one which strikes N47°E and one which strikes N43°W.

Fig. 12 shows a proposed building site and the approximate location of all of the historic and prehistoric sinkholes that are known to have occurred in the immediate site vicinity. Also shown in Fig. 12 are bands representing the inferred location of joints in the limestone surface. These bands were constructed using the strike of the lineaments presented in Fig. 11. All of the site area crossed by the bands and particularly those areas containing the intersection of two bands is suspected of containing a breach in the confining layer.

If the building can be positioned to avoid all of the suspect areas and is outside the zone of influence of a potential sinkhole, the foundation exploration and design proceeds normally. However, if the building must be located near or over a suspected breach, a much more extensive subsurface exploration and testing program is required.

In many cases it is possible to begin the subsurface investigation using such geophysical techniques as ground-penetrating radar, EM conductivity, or seismic surveys.[3-7] All of these techniques can detect anomalies in the subsurface profile. Fig. 13 is an example of a suspected breach located using ground-penetrating radar.

After all of the geophysical data has been reviewed and anomalous

areas located on the site map, a drilling and testing program is planned for the site. Within the areas of the site not located above a potential breach in the confining layer or paleosink in the limestone surface, the test borings or soundings are spaced conventionally. However, at least one of the test holes in this area is advanced into bedrock, i.e., into the confining layer, so that the unaffected site stratigraphy can be documented.

Within the suspect area of the site, the test holes are spaced much closer together, e.g., at each column location, and all of the holes are advanced to the top of the bedrock complex. Although Standard Penetration Test borings are still drilled on almost every major building site in central Florida, the cone penetrometer is becoming the sounding method of choice for most sinkhole investigations.[8,9] The advantages of the cone penetrometer are speed and sensitivity to subtle changes in soil density. The electric piezocone is particularly attractive for sinkhole investigations because it can detect and document slight downward hydraulic gradients.

Fig. 14 illustrates a pore pressure profile within a sand-filled breach area where the downward hydraulic gradient is 1.3 ft/ft (0.4 m/m). Essentially all of the hydraulic head is dissipated in downward flow through the breach. Accurate water table measurements are also important on sites being investigated for
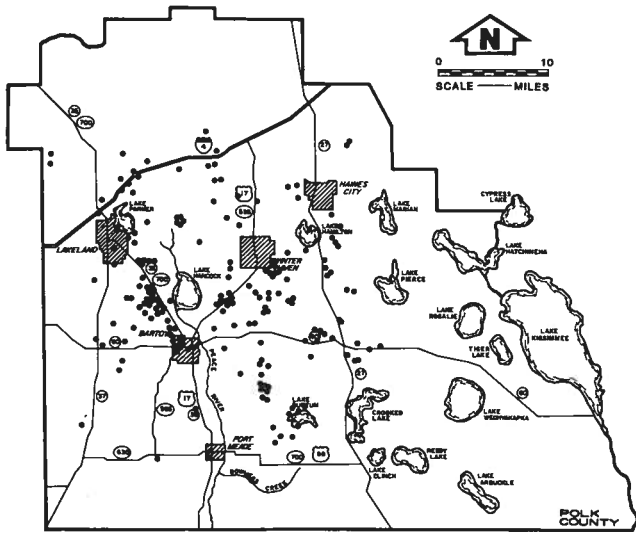
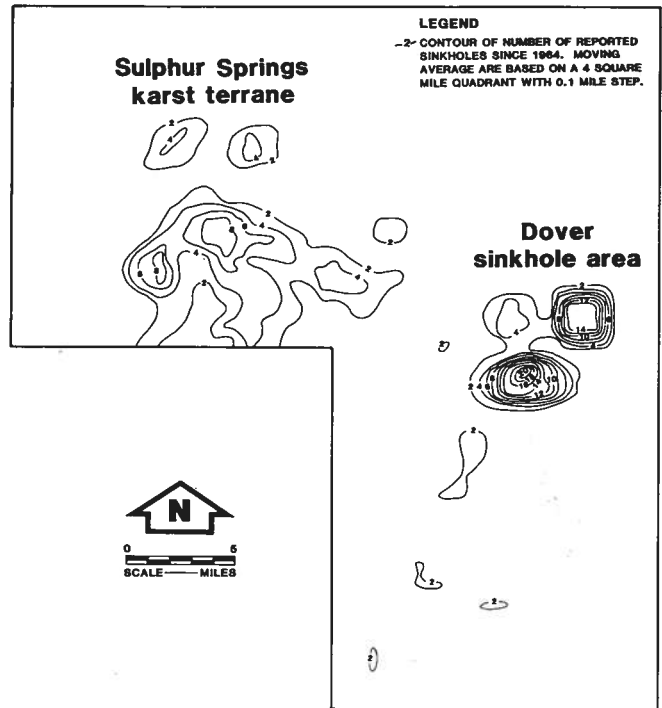Fig. 9 — Historic sinkholes in Polk County.

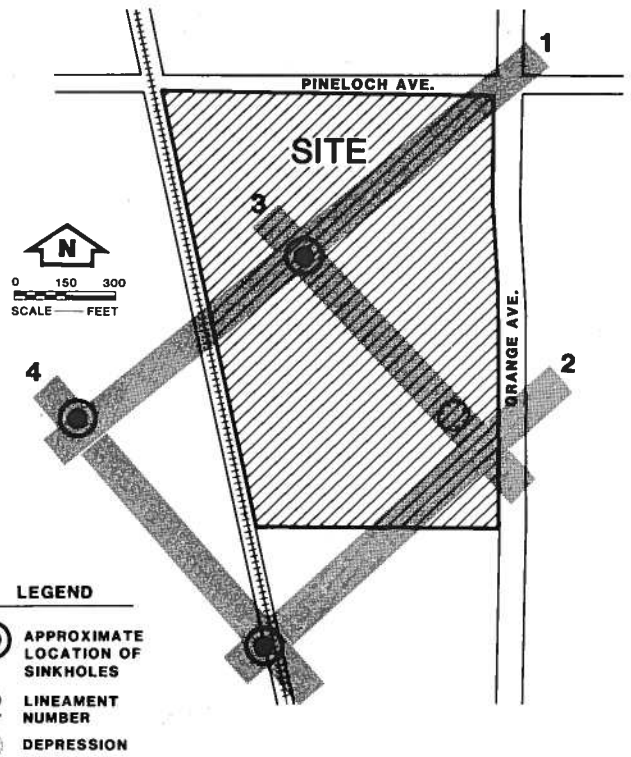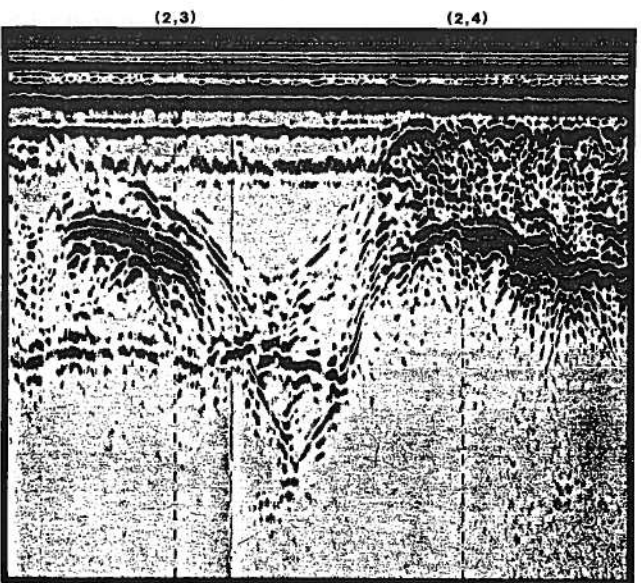Fig. 10 — Moving average analysis of modern sinkholes in Hillsborough County.
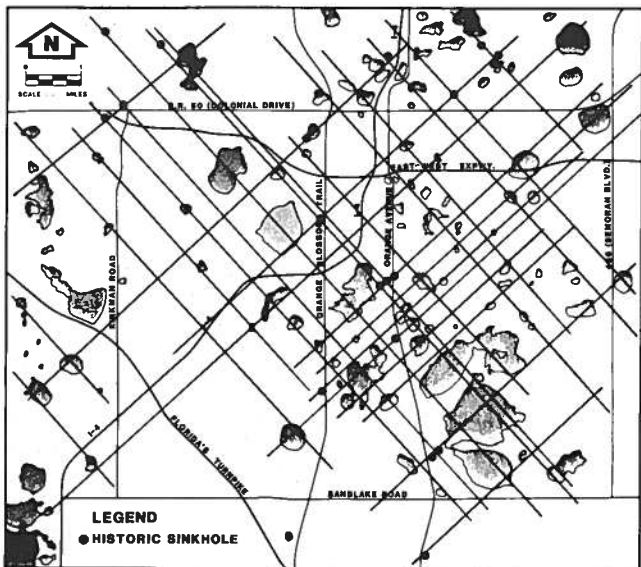

Fig. 11 — (middle left) Partial lineament map for South Orlando.

Fig. 12 — (bottom right) Lineament map for project site.

Fig. 13 — (bottom left) Ground-penetrating radar printout of a paleosink near Sanford.

sinkhole potential. A shallow monitor well is generally left at each test hole location for determining the direction of groundwater flow on the site. Depressions in the water table, as illustrated on Fig. 1, are definite indicators of breaches in the confining layer.

Foundation design for sinkhole-prone sites

If a detailed investigation of a site does not disclose any breaches in or ravelled conditions above the confining layer, building foundation design proceeds normally. If a breach or ravelled conditions are discovered, the building is generally moved to avoid the zone of influence of the breach. The zone of influence is estimated based on historical data as well as the thickness of overburden.

Under certain circumstances, such as when the limestone is at a shallow depth, where there is little difference in piezometric levels between the surficial aquifer and limestone aquifer, or when the expected cost of a failure is low, it may be possible to leave the building at its desired location and either design the foundation to span a potential sinkhole or plug the breach.[10] Fig. 15 is a cross section through a breach that was grouted;[11] the cost of the investigation and grouting was over $200,000. The author does not recommend grouting except in very unusual circumstances.

Foundation design in non-sinkhole-prone karst areas

Where the breaches in the limestone are filled with clayey soils, where there is no significant downward hydraulic gradient, and where historical sinkholes are nonexistent, the potential for sinkhole development is considered to be extremely remote. Nevertheless, foundation design for major structures in these areas presents unique challenges.

Fig. 16 presents the site plan and the building layout for a major public facility in Tallahassee, Florida. Differential settlement for the proposed structure was limited to ½ in. (12.7 mm).

Twelve Standard Penetration Test borings were drilled at the locations shown in Fig. 16. The depth to bedrock for the 12 borings varied from 56 to 174 ft (17 to 53 m). The subsurface profile consisted of stiff to very stiff clayey sands to sandy clays overlying weathered limestone. A contour map of the bedrock contact, as extrapolated from the 12 test borings, is presented in Fig. 17. A deep paleosink is indicated in the northwest corner of the site.

Relative cost and performance comparisons between shallow and deep foundations, based on the data generated by the 12 test borings, indicated that a pile foundation would be the more suitable and economical foundation type for the proposed structures.

To document that a minimum of 16 ft (4.9 m) of sound bearing material was present beneath each pile tip, an additional test boring was performed at each major column location.

A contour map of the bedrock contact extrapolated from the 12 original test borings and the additional 110 borings performed at the major column locations is presented in Fig. 18. The additional test borings disclosed three additional paleosinks, all of which are located within the proposed construction area.

Although 12 in. (305 mm) diameter pipe piles were recommended for the project, the contractor convinced the owner and architect that he could complete the job more economically using a composite pile, which was to consist of a 10.5 in. (267 mm) diameter pipe section attached to a mandrel-driven step-tapered shell.

During the first few weeks of production driving, several piles had to be abandoned because the length of the pipe section, as estimated from the test boring performed at the center of the pile cap, was too short and the mandrel-driven step-taper section could not be extended. In one of the pile caps, the difference in tip elevation between piles on opposite sides of the cap was greater than 50 ft (15 m). At

another location, the difference was greater than 60 ft (18 m).

To avoid similar occurrences on the remainder of the job, the contractor completed the job using 12-in. (305-mm) pipe piles. Except for the delays associated with extending the pipe piles and some minor difficulties with curved piles, the contractor was able to successfully complete the job using the 12-in. pipe piles within a reasonable time. A contour map showing the top of bedrock, as extrapolated from the borings and the pile driving logs, is presented in Fig. 19. Comparison of Fig. 18 and 19 indicates that even closely spaced borings do not always disclose an accurate picture of subsurface hazards.

Nevertheless, in the area of this project the author's firm always recommends borings at each column location and develops bedrock contour maps of the weathered rock surface prior to completing foundation design. Design recommendations then take into consideration the possibility that not all of the problem areas have been detected. On most recent major projects in the area, we have recommended drilled shafts (caissons) as the most suitable and economical foundation alternative. Test borings are extended at least two diameters below the base of the shaft to document the absence of cavities.

Conclusions

Karst, especially when covered with thick deposits of clastic sediments, presents unique challenges to foundation designers. Much more intensive field investigations are required for major structures overlying deeply buried karst than for similar structures overlying most other rock formations. For deep foundations, the depth to bedrock contact may vary considerably within relatively short distances, even within the same pile cap. Only piles that can be easily extended or drilled shafts should be used in this environment.

Piping of erodible sediments into solution cavities in the limestone through breaches at the surface of the rock has caused catastrophic failures at many sites in north and
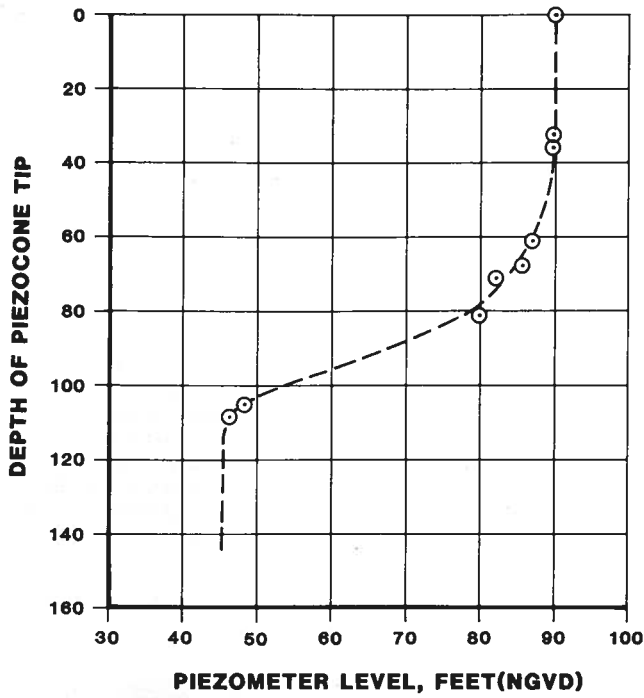
Fig. 14 — Piezometric level as a function of depth within very soft, sand-filled breach in Hawthorn formation.
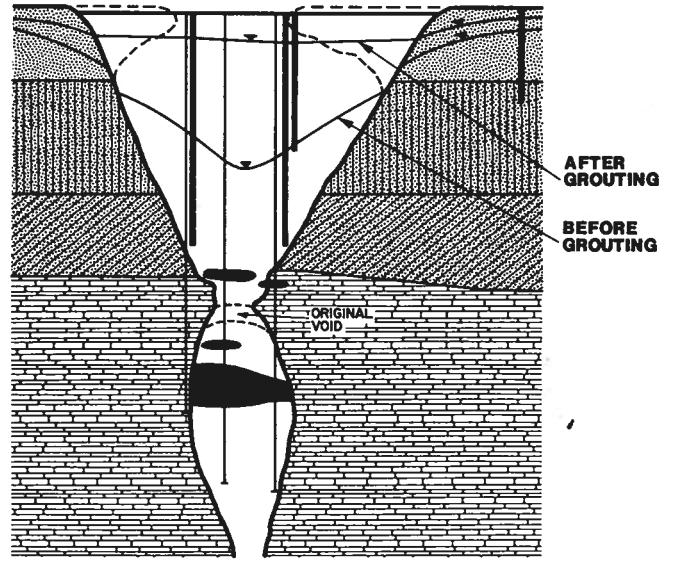

Fig. 15 — Cross section of paleosink showing grouting results and water levels before and after grouting.
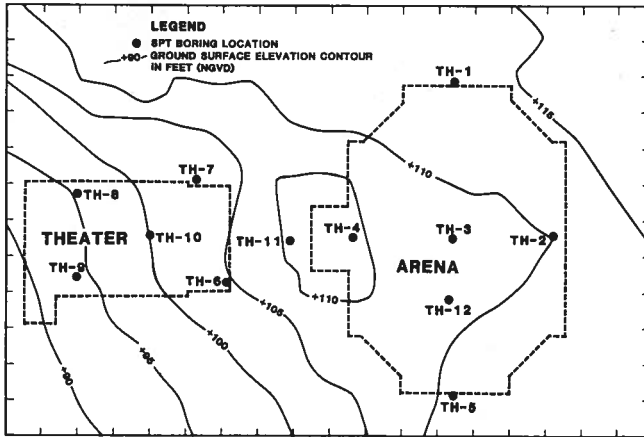

Fig. 16 — Layout of proposed structures for Tallahassee project.
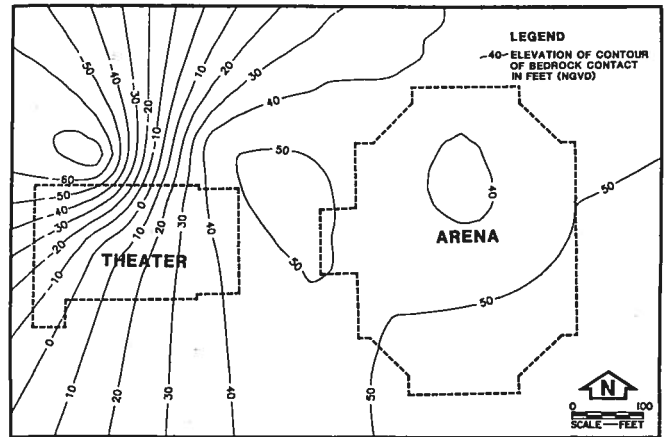

Fig. 17 — Contour map of bedrock contact for Tallahassee project based on 12 borings.
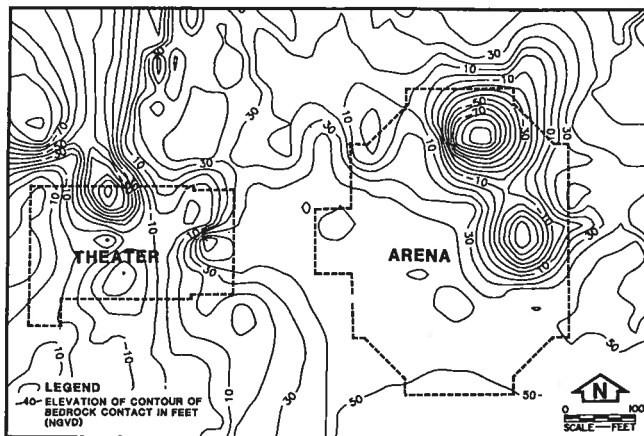

Fig. 18 — Contour map of bedrock contact for Tallahassee project based on 122 borings.
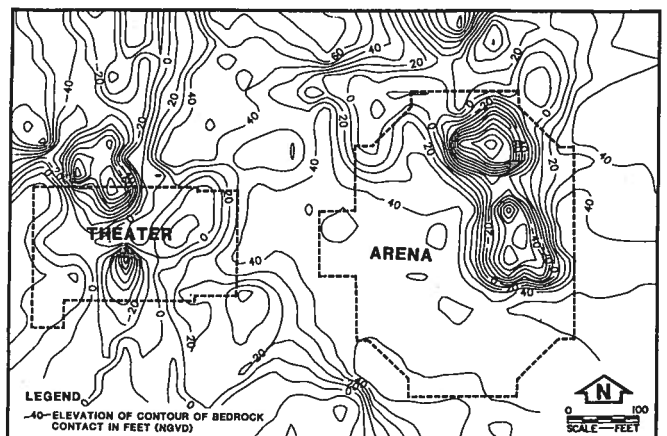

Fig. 19 — Contour map of bedrock contact based on all borings and pile-driving logs.

central Florida. A thorough investigation of these sites to determine the location of these breaches using both indirect and direct techniques is a prerequisite for proper foundation design.

Evaluating sites for sinkhole potential requires evaluating historical data on sinkhole occurrences and a knowledge of the geology and hydrogeology in the area. Risk analysis using an annualized rate of sinkhole occurrence per unit area is a useful method for screening and selecting sites for future development. Geophysical methods, particularly ground-penetrating radar, supplemented with conventional exploration techniques, are the primary tools used in locating areas of potential sinkhole activity within a specific site.

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Selected for reader interest by the editors.

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