Planning and Design Considerations in Karst Terrain

J. A. FISCHER
Geoscience Services
Bernardsville, New Jersey, USA

R. W. GREENE
Storch Engineers
Florham Park, New Jersey, USA

R. S. OTTOSON
Ottoson & Ottoson
Cranford, New Jersey, USA

T. C. GRAHAM
Lanid Corporation
Parsippany, New Jersey, USA

ABSTRACT / This article discusses the various steps that the authors feel are necessary to the successful progression of an engineered project sited in karst terrain. The procedures require a multidisciplined approach with liaison and cooperation among the various parties to the project.

Initially, the prospective owner must have sufficient understanding of the potential engineering problems to incorporate the engineering geologist into the early stages of any planned acquisition. The first step in an investigation should include a review of the available geologic information, aerial photo interpretation, consultation with the State Geological Survey, and a geologic reconnaissance of the prospective site and surrounding area.

A go-no-go decision as to purchase can often been made at an early time. Although, in some instances, more study is needed for a particularly intriguing property.

The second stage should consider the various planning alternatives that are feasible based upon the limited available information. At this stage planning/purchase decisions can be made as to purchasing options, value of the property, design constraints, and the possible economic penalties that could be associated with the potential site construction. Various planning and construction alternatives should be considered in this phase of the work.

The third stage should include a site investigation program of moderate size, consisting of test pits and/or exploratory borings. The borings should be drilled using water as the drilling fluid, with an experienced crew and qualified technical inspection. The authors find the use of geophysical techniques can be extremely misleading unless used in conjunction with exploratory drilling. Successful evaluations using geophysical procedures occur only under ideal conditions.

The geotechnical viability of the plan and preliminary design should be investigated in the fourth phase. Additionally, the physical parameters required for the design of structures founded atop cavities can be obtained at this time. Several support schemes which incorporate cavity roof thickness, rock strength, and cavity space are discussed.

Possible construction procedures include excavation and dental concrete, grouting, piers or piles to sound rock, or moving to another area. The relative economies of these procedures are discussed in relation to the size and depth of the soil or rock cavity, possible future cavity formation, magnitude of loading and acceptable safety factors.

Introduction

This article attempts to describe the geotechnical aspects of what the authors believe are the appropriate procedures to employ in multi-phased, multi-disciplined studies for projects which may be located in karstic locations. In using the term *geotechnical engineering,* we prefer to consider it in the true meaning, not as it is sometimes used, as synonymous with soil mechanics or foundation engineering.

The carbonate rocks we will discuss herein are hard crystalline materials, when unweathered. They are the Cambro-Ordovican formations found in the valleys of the Appalachian range. They are found from Ontario to Alabama, causing a variety of problems, but still not well recognized as being of concern to construction and environmental well being. The many physical features resulting are well known: Mammoth Caves, Luray Caverns, Shenandoah Caverns, Natural Bridge(s), Crystal Cave, Howe Caverns, etc.

These carbonate rocks were deposited some 400 to 500 million years ago at the edge of the North American continental land mass, as it then existed. The continental margin was folded and faulted during the closing of the proto-Atlantic Ocean, and the carbonates were subsequently deposited within the fold-produced valleys. The thickness of the Appalachian carbonate deposits range widely, from less than a few feet to in excess of one thousand feet. Subsequent deformation along the edge of the continent resulted in

Environ Geol Water Sci Vol. 12, No. 2, 123–128

extensive faulting, numerous shear zones, and in some instances recemented breccias. In many instances extensive deposits of carbonates were moved in fault blocks, fractured anticlines, and decollements, to their present positions. Water flow through these many fractures and faults has resulted in the formations of solution cavities and channels. Migration of unconsolidated overburden materials into these cavities and channels manifests itself in ground surface subsidence and dolines.

Construction above these hard crystalline formations can result in severe geotechnical problems. The causes and solution to these problems can be quite different than those of the more well know, more geologically recent, limestones of, for example, Florida or Puerto Rico. The authors' experiences in dealing with these "hard" carbonate rocks are in or near the Appalachians, however, similar deposits are found in the western United States, Canada, and South Africa, and we believe the results of our studies are broadly applicable.

For purposes of this discussion we can attempt to separate the various aspects of a multi-scope, geotechnical investigation of a site into coherent segments. Obviously in the real world some phases may nearly (or completely) disappear. There is almost always overlap, and sometimes budgetary or time constraints require the combination of the discrete segments, and too often, their compression into an almost amorphous mass of "do it now." From a chronological standpoint the phases of a project we would like to see are:

1. Prepurchase site evaluation
2. Prepurchase planning and conceptual design
3. Site investigation
4. Planning, layout, and design
5. Additional site studies where warranted
6. Final layout and design where necessary
7. Construction inspection and design changes where necessary

From a technical and presentation standpoint it is easier to categorize those chronological segments into:

1. Prepurchase Site Evaluation
2. Planning
3. Site Investigation
4. Geotechnical Engineering

It is these later four segments which we will use as the format of this article.

Prepurchase Site Evaluation

For the knowledgeable developer the best return on his investment occurs when the possible geologic hazards at a site, such as doline occurrence, are investigated prior to sinking money into a valueless site (or into a bottomless sinkhole). Unfortunately very few real estate development groups have the knowledge or the inclination to worry about geologic hazards until it is time to "start construction."

A great deal of information, suitable for preliminary evaluation within the carbonate rock formations of the East Coast, is available through Federal or State Survey data (our local State Surveys have provided invaluable assistance in many instances). Although different names abound, it is frequently possible to correlate formations, hence properties and performance, from state to state. Typical commonly available information may include:

1. Water-bearing potential (well yields) of a formation; generally the higher the water-bearing potential and greater the probability and density of cavities or shear zones;
2. The existence of caves or documented solution activity;
3. Grain size of limestones or dolomites (textural classification has sometimes been correlated with porosity, the larger the grain size the greater the susceptibility to solution);
4. The existence of faults or other macrogeologic forms of distress; and,
5. Unconfined compressive strength of sound rock.

Using these data, together with a site reconnaissance, and an inspection of aerial photos, many times allows the experienced engineering geologist to develop a realistic appreciation of the problems that can be faced in areas underlain by carbonate rocks. As will be subsequently discussed, these concerns can include much more than doline formation.

This preliminary evaluation can lead to a variety of decisions by the prospective owner/investor. He may decide to eliminate the site from further consideration, with only this small investment in time and money. If only a portion of the site can be developed economically, as a result of cavity-prone rocks, a reduction in the purchase price of the property can result. An additional alternative can be to perform further, more definitive, geological studies to better define the limits and scope of the problem.

Planning

If the areal extent of the sinkhole problem is known it may be possible to move major structures away from the areas of solution-prone carbonate rocks to areas underlain by sound materials. Noncritical facilities, such as golf courses, parks, ball fields and hiking trails, even roadways or parking areas, (which are lightly loaded, and reasonably economically repairable) may be sited in the doline-prone areas.

Our experience with sinkhole development in the older carbonate rocks is that the formation time is relatively slow. Hence doline formation is not life threatening as long as one is aware of the possibility of occurrence and some care is taken in observing the areas of possible dissolution.

If future inspection, maintenance, or repair costs are anticipated they should be incorporated in project financial evaluation or planning.

Building up, rather than out, or altering the configuration of a proposed development are also planning-type solutions which can be implemented in a project.

Detention basins to control runoff are mandated by law in many "environmentally aware" communities. The use of such detention basins in carbonate areas can only exacerbate the problem by increasing water pressure and flow in subsurface soils; thus increasing the possibility of soil movement and eventual development of dolines or open channels in the detention basin and adjacent areas. Unlined detention basins in doline-prone areas should be avoided. Conversely, it is possible to take advantage of potentially large well yields from solution-prone carbonates or perhaps utilize aesthetically, carbonate rock pinnacles, disappearing streams, etc., keeping in mind the potential for migration of subsurface soils and the ensuing problems associated with uncontrolled groundwater movement.

We cannot overemphasize the need to minimize or even eliminate water flow into the subsurface in the vicinity of structures where the presence of soil voids are known or suspected. Handling water from roof downspouts, parking and roadway areas, catch basins, flow along utility line backfills, and similar, are all sources of potentially deliterious subsurface water flows.

Site Investigation

At some stage (or perhaps in several phases) an on-site investigation must be made. For planning and design purposes the lateral extent of the cavity-prone rocks below the site should be known. Cavity size, location and distribution of soil voids, material properties, rock surface configuration, and water quality and quantity may all be required geotechnical information.

Many indirect procedures have been advanced for the detection of subsurface cavities which have not yet become dolines. These include geophysical studies, such as seismic refraction or reflection, gravity and conductivity techniques, and ground penetrating radar. All can be useful in a certain specific situation, however, one must have a good understanding of the nature of the subsurface before utilizing any form of indirect sensing. Even air-percussion drilling, at, for example, each column of a structure, albeit quite fast, in most instances does not provide sufficient data to realistically interpret the subsurface conditions encountered, without the aid of judiciously placed test borings and qualified technical inspection of the percussion drilling operations.

While attempting to utilize as many site investigation tools as possible the authors believe there is no substitute for carefully drilled test borings, qualified full time inspection, experienced and careful drillers, and large diameter Christensen-type double tube core barrels. This is the only meaningful way to develop definitive measures of the geotechnical properties of the subsurface at a site. Other procedures can be useful in some instances, for example, to correlate between test holes, but not as the only investigative tool employed at a carbonate rock site. Observing a full 5-foot core run—the clay seems, stained joints, weathered cavity sides; noting the amount of water loss in a clayey residual soil; seeing the variations in rock coring times; or watching the drill rods actually fall through a void are immeasurable aids to one's understanding of the subsurface.

The rock section shown on Figure 1 represents the data obtained during the drilling of a series of grout holes only 10 feet apart. As can be seen on this figure, rock depths varied 20 or more feet in the 10 foot horizontal distance between borings. The amount of grout placed in these exploratory holes varied from two cubic feet of one part Portland cement: one part water grout, to 140 cubic feet of accelerated (as fast as 15-second set time) grout in adjacent holes. It is not difficult to imagine the difficulty any geophysical procedure would have in attempting to quantify subsurface conditions of this nature.

Thus, it is believed that a judicious program of subsurface exploration (with allowances for flexibility as a result of information obtained during the field studies) using experienced personnel, rotary wash boring drilling equipment, and a double tube core barrel represent the only positive way to identify the nature and extent of the solutioned carbonates with which we are familiar. Without a reasonably detailed knowledge of the subsurface, performing the engineering phase of a project becomes difficult to imagine, as well as extremely costly, as a result of either overconservatism or the inability to anticipate expensive problems.

Geotechnical Engineering

Sinkhole formation is one of the more spectacular effects of solution-prone carbonates underlying a site.

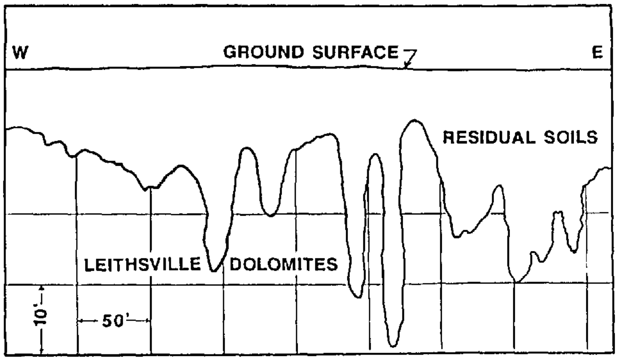

Figure 1. Section-Leithsville Formation, Peapack, NJ.

However, many other problems must be considered in site development and design.

The likely great irregularity of the rock surface must be considered in foundation design and excavation operations. We may blast a pinnacle of rock for a sewer line, while 20 feet away excavate a water-softened mass of unstable clays which resulted from dissolution and soil-erosion.

What manner of differential settlement could be expected if one part of a structure is supported on firm residual soils overlying shallow competent shales, while another portion is underlain by 25 feet of moderately firm residual soils and then 35 feet of very soft residual clays with a water content of 50 percent (see Fig. 2) overlying solution-prone limestones.

If one has a realistic understanding of these subsurface irregularities, it is possible to devise solutions, or estimate costs whether the proposed structure is a simple 1-family house or a massive dam. Thus the importance of an appropriate site investigation cannot be overemphasized.

Another area of concern in solution-prone carbonates is the possibility of groundwater contamination. Rather than having the advantage of soil filtering, geochemical absorption or nominal dilution, contaminant slugs can travel quickly and relatively undiluted through a cavity to a water supply well. Conversely, of course, solution-prone carbonates are often an excellent source of groundwater, if a well penetrates a shear zone, solution channel, or cavity.

We have also experienced high radioactivity levels in the residual soils and rocks of several New Jersey carbonates located in close proximity to more well accepted sources of radioactive ores. Although the conventional depositional conditions for a marine carbonate are not considered ideal for uranium and thorium mineralization, radon testing in a number of carbonate formations has yielded higher than normal readings. Whether the radioactivity results from movement, along fault or shear zones, of groundwater bearing radioactive elements, or whether the radioactivity results from simple erosion of the nearby mineralized Precambrian rocks into the carbonate depositional environment is not known at this time.

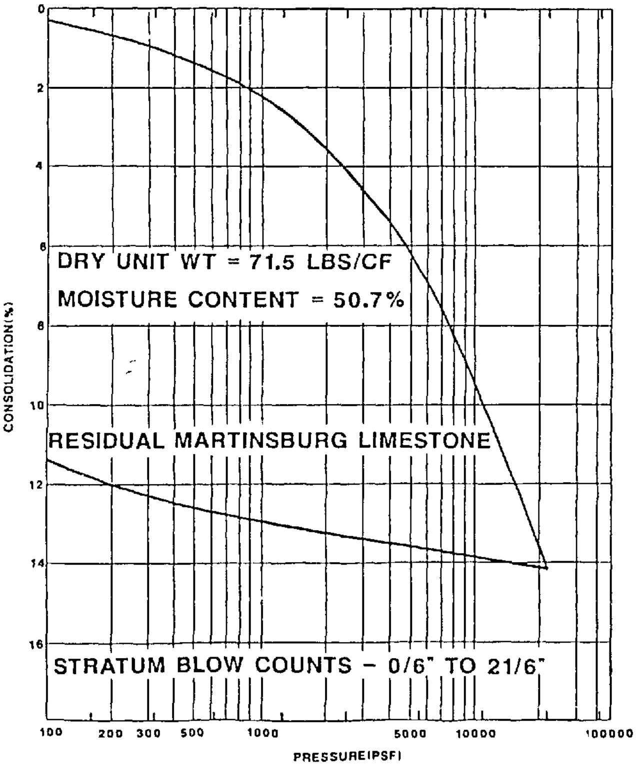

Figure 2. Consolidation test data (ASTM D2435). Yellow brown silty clay with sand and gravel.

Some of the more viable foundation solutions, if soil voids and cavities are found below planned construction sites, include: (1) Excavating to rock, filling any cavities large enough to be detrimental to the provision of adequate foundation support with concrete, and returning to grade with a controlled structural fill; or (2) Installing caissons or piles to solid rock. In this second instance test probes should be drilled to assure that adequate support is available below the caisson or pile. Recommended bearing pressures should consider the expected or allowable thickness of rock that may be above a cavity. Typical design formulas are discussed subsequently. The erratic nature of the subsurface topography must always be considered in both design and field installation. Grouting is a well recognized procedure. Either cement, chemical, or accelerated grout have been used to fill cavities, or prevent seepage from reservoirs.

Grouting may be used to: (1) Fill cavities, sometimes extremely expensive; (2) Merely to provide load bearing columns for lightly loaded areas (for example,

BEAM THEORY

$$L = \sqrt{\frac{2Tt}{wF}}$$

PLATE THEORY

$$a = \sqrt{\frac{Tt}{6BwF}}$$

Values of B for various b/a values with Poisson's ratio of 1/3

b/a	B
1.0	0.0513
1.2	0.0639
1.4	0.0726
1.6	0.0780
1.8	0.0812
2.0	0.0829

For ratios of b/a >2.0 beam theory is a close approximation.

Figure 3. Design Formula: T = span length; t = slab thickness; w = unit weight; F = safety factor; a = shorter lateral dimension; b = longer lateral dimension; B = see table above.

sanitary sewer lines, houses, or similar); or (3) As a membrane-type seal.

There are a number of procedures that can be used to estimate the supporting capacity of layered media overlying a cavity. Four alternatives are discussed herein. All, however, require a good understanding of rock properties and the dimensions of the cavity.

The simplest is a semi-empirical approach that can be derived from Barton and others (1974, 1977) in which correlations of the type and amount of permanent support required in underground excavation are made with a rock mass quality indicator, *Q*. The *Q* value is dependent upon a number of insitu rock characteristics; the RQD index, the number of joint sets, the roughness of the weakest joints, the degree of filling or alteration along the weakest joints, and two further parameters which account for the rock load and water inflow. This approach requires not only well defined site characteristics but also assumes that no exterior loads are applied to the cavity roof. Thus we believe it would be most prudent to combine the results with one or more other analytical procedures.

That next approach considers that any cavities encountered in the rock at the site could be represented by a mathematically equivalent simple plate or beam. These types of analyses require a number of assumptions. The assumptions include: the existence of a rock slab(s) extending over the entire cavity, that the roof slab has uniform thickness, that it has no vertical joints or fractures, that there is no bond between the roof slab and the (other horizontally bedded) rock above, that the roof slab and the layers above are internally homogeneous, isotropic, elastic media, that no confining stresses exist at the edges of the slab. If the assumptions can be met (or are at least reasonable) then the roof slab can be assumed to be either a uniformly loaded beam fixed at both ends or a uniformly loaded rectangular plate fixed on all sides. Both assumptions result in relatively simple elastic theory relationships (see Fig. 3 from U.S. Army Corps of Engineers 1961).

$$t = \sqrt{\frac{Lw}{2at}}$$

Figure 4. Room & Pillar Theory (Dismuke 1976, Kitlinski 1969).

It should be noted however that the formulas shown on Figure 3 must be used with care as they were developed for unloaded, unsupported cavities (using simplified elastic theory assumptions). To attempt to use these formulas for any project, the "beams or plates" of rock must be "uniformly loaded" by the foundations. Furthermore, it is also necessary to assume that the weight of the rock *(w)* is the actual unit weight of the carbonate plus the imposed loading. While conservative in most instances, this assumption can only be considered reasonable for a spread or large caisson-type footing, with which a "punching" failure will not occur.

The third approach depends partially upon a knowledge of the rock and cavity characteristics at the site, and is basically an empirical procedure reported from work in Pennsylvania carbonates (Dismuke 1976, Kitlinski 1969).

The relationship shown on Figure 4 was developed for mined areas with an assumed room and pillar configuration, i.e., the cavity roof is supported at four points. Although apparently not intended to incorporate consideration of a loaded area above the cavity, this approach has reportedly been successfully used in locations that the authors believe are underlain by Cambro-Ordovician carbonates. Caisson loadings of more than 100 tons have been used with the equation shown on Figure 4. The magnitude of safety factor used is not known to the authors.

Not economically viable for small projects, but certainly feasible for major studies is the use of a geomechanical model (Kulhawy 1978) and a finite element computer model.

The geotechnical engineering portion of any project should not stop with the start of construction. It should be obvious from the previous discussion that sites in karst terrain are most difficult to characterize and to develop a satisfactory knowledge of all the problems that one may face. Rather than "overkill" the field investigation, the prudent design team allows for construction inspection and incorporates the ability to make field changes that reflect the knowledge gained during construction activities. These changes may result in both economic and time penalties, hence they must also be considered in the planning and financial aspects of a project.

Summary and Conclusions

The existence of solution-prone carbonates below a construction site need not be cause for instant panic, nor should they be neglected until a sinkhole develops below a structure. A prospective site in doline terrain is not cause for automatic abandonment, however, the owner/design team should be realistically aware of the possible problems:

1. The magnitude and extent of the geologic concerns at the site.
2. The possible variations in stratigraphic conditions (thickness, attitude of bedding, fault, or shear zones).
3. Physical properties of the subsurface soils, rock, and groundwater at the site.
4. The availability of possible planning or engineering solutions.
5. The economic and time penalties that can result from the erratic and unusual subsurface.

With a judicious use of regional geologic data, onsite studies, and a full integration of the geotechnical engineering concerns into planning and design, it is possible to develop sites atop solution-prone rocks. Without the appropriate geotechnical foreknowledge it is possible to make extremely costly mistakes.

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