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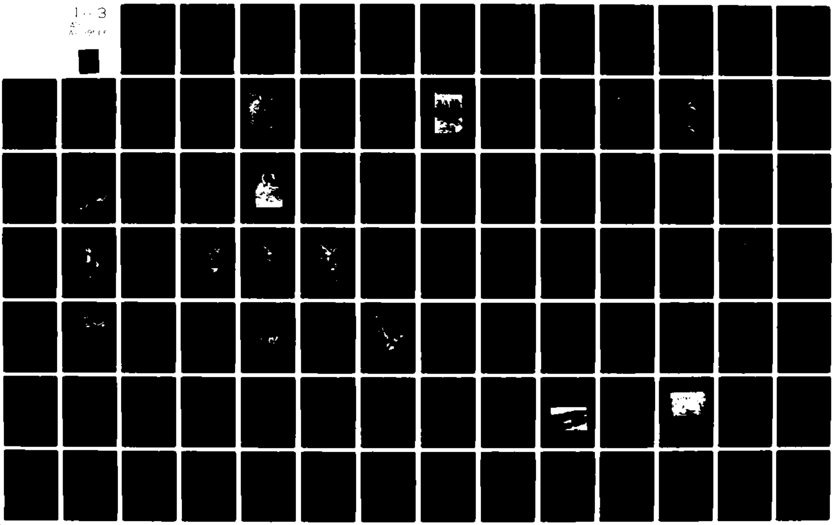

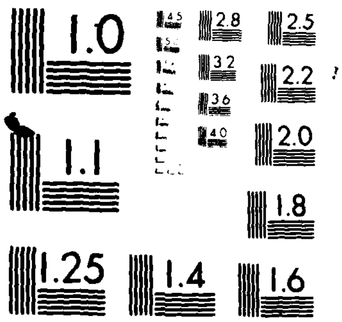

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Foundation Considerations in Siting of Nuclear Facilities in Karst Terrains and Other Areas Susceptible to Ground Collapse

Prepared by A. G. Franklin, D. M. Patrick, D. K. Butler, W. E. Strohm, Jr.
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ABSTRACT

Roughly one third of the continental United States is underlain by rocks that may have a potential for ground collapse as a result of solution processes, pseudokarst conditions, or mining activity. The purpose of this report is to review and describe the current state of knowledge in dealing with engineering problems arising from these sources where they might affect the safety of nuclear facilities.

The subject matter of this study includes the integrity and proper functioning of foundations and water-retaining structures, engineering measures to deal with cavities and related conditions, and investigations to develop the information needed for those purposes. Thus, four major functional issues are identified, and these are taken as the conceptual framework for the study: (1) Prediction. Major considerations are the geological conditions and processes leading to development of cavities and related features, and consequent ground collapse; geographical distribution of such conditions; and indicators, or warning signs, that the potential for ground collapse requires evaluation at a particular site. (2) Detection. Methods of exploration to detect and delineate possible cavities and associated features; exploration planning; conventional site investigations; remote sensing methods; hydrological investigations; geophysical methods; and probabilistic considerations. (3) Evaluation. Mechanisms of ground collapse and sinkhole development; the nature of threats to structural foundations and water-retaining structures; analysis of stability; critical sizes and depths of cavities. (4) Treatment. Engineering remedies for problem conditions under structural foundations and reservoirs; treatment of sinks, solution-widened joints, solution cavities, and mined openings; potential problems caused by treatment; post-construction monitoring; provisions for future treatment.

Discussions of these issues and of approaches to resolving them include descriptions of methodology and currently available techniques, principles of operation, applicability, and limitations. Sources of additional information are identified in an extensive list of references.

CONTENTS

Page

CHAPTER I: INTRODUCTION 1

CHAPTER II: THE ORIGINS OF UNDERGROUND OPENINGS 4

THE KARST ENVIRONMENT 4

Definition 4
Morphology 4

Surface morphology 4
Subsurface features 5
Other features 7

Origin and Classification of Soluble Rocks 8

Carbonate rocks 10
Evaporates 11

Origin of Solution Features 14

Mineralogy and geochemistry 14
Weathering 15
Geomorphology 16

Cave Deposits 18

Chemical deposits 19
Detrital deposits 19

Pseudokarst 21

Surface forms 21
Subsurface forms 21

FACTORS AFFECTING THE DEVELOPMENT AND POTENTIAL HAZARD OF SOLUTION FEATURES 22

Geological Factors 23

Rock Properties 23
Mineralogy 23
Lithology 23
Diagenesis 23
Rock mass properties 24
Stratigraphy 24
Structure 24
Discontinuities 25
Strength 27
Environmental Factors 27

Surface hydrology 27
Subsurface hydrology 29
Climate 29

Page

GEOGRAPHICAL DISTRIBUTION OF UNDERGROUND OPENINGS AND SOLUTION FEATURES IN THE UNITED STATES 30

Areal Distribution of Karst and Pseudokarst Features 30
Summary by Physiographic Province 36

Newer Appalachians 36
The Appalachian Plateau 39
Interior Low Plateaus 40
Ozark and Ouachita Plateaus 43
Atlantic and Gulf Coastal Plains 43
Great Plains 45
Other karst and pseudokarst areas 46

Other Underground Openings 47

POTENTIAL INDICATORS OF SUBSURFACE OPENINGS 49

CHAPTER III: SITE INVESTIGATIONS - CONVENTIONAL METHODS 54

PLANNING 54
HYDROLOGICAL INVESTIGATIONS 57

Piezometers 58
Flow Tracing 58
Water Pressure Tests 60

TEST GROUTING 61
REMOTE SENSING METHODS 61

Force Field Sensors 62
Radiation Sensors 62
Aerial photography 63
Scanning devices 64

DRILLING AND EXCAVATION 66

Accessible Excavations 66
Drilling 68

BOREHOLE SURVEYS 71
PROBABILISTIC CONSIDERATIONS IN PLANNING AN EXPLORATION PROGRAM 78

Random Search 80
Uniform Search with Point Grids 82
Inferences from Uniform Search 89
Multiple-Stage and Sequential Search 93
Optimal Nonuniform Search and Gradient Methods 95
Random Process Models 95

CHAPTER IV: SITE INVESTIGATIONS - GEOPHYSICAL METHODS 96

CHARACTERISTICS OF GEOPHYSICAL METHODS 96

	Page
RESPONSE OF GEOPHYSICAL MEASUREMENTS TO CAVITIES	97
Principles	97
Past Cavity Detection Efforts	100
Seismic Methods	100
Refraction	100
Reflection	103
Fan shooting	107
Subsurface seismic methods	110
Acoustic resonance	115
Electrical Resistivity Methods	116
Resistivity sounding	119
Resistivity profiling	120
Pole-dipole surveying	121
Subsurface methods	123
Microgravimetric Methods	123
Electromagnetic (EM) Methods	127
Surface ground probing radar	128
Borehole EM methods	129
RECONNAISSANCE SURVEYS FOR CAVITY DETECTION	132
Methodology	132
Geophysical Reconnaissance Programs	133
Presentation of Data	137
HIGH-RESOLUTION SURVEYS FOR CAVITY DELINEATION	138
Methodology	138
High-Resolution Survey Programs	140
Crosshole surveys in a systematic drilling program.	140
High-resolution surveys for foundations of structures	141
Anomaly delineation surveys	143
CHAPTER V: EVALUATION OF FOUNDATION CONDITIONS	147
NATURE OF HAZARDS	147
Solution Cavities and Sinkholes	147
Collapse mechanisms	147
Sinkhole pipes and filled sinks	149
Contributing or modifiying factors	151
Subsidence and Collapse over Mined Openings	155
Mechanisms of failure	155
Sinkholes and subsidence troughs	155
Kind and depth of subsidence	155
Effect of overburden thickness	156

Page

Time of occurrence 159
Effect of precipitation 159
Types of overburden strata 159
Subsidence troughs 161

Mine roof caving 166

Collapse Potential from Other Types of Mining 169

CRITICAL DEPTH AND SIZE OF OPENINGS 169

Natural Cavities 169
Mined Openings 175

EVALUATION OF FOUNDATION SAFETY 176

Conditions Affecting Structural Foundations 176

Solution of bedrock surface 177
Filled sinks 178

Erosion potential 178
Bearing capacity and settlement 179

Cavities below bedrock surface 179

Potential for enlargement 179
Effect of infilling materials 180
Cavity stability 181
Mined openings 186

Conditions Affecting Water Retention Structures 187

Embankment foundations 188
Reservoir safety 188
Reservoirs over mines 190

CHAPTER VI: FOUNDATION TREATMENT AND MONITORING 191

TREATMENT METHODS 191

Filled Sinks and Solution-Widened Joints 191

Foundation areas 191
Reservoir areas 191
Seepage control in other areas 193

Solution Cavities 195
Mined Openings 195

Support methods 195
Filling methods 199

Improvement of Seismic Stability 199
Potential Problems from Grouting and Filling 202

MONITORING 203

Groundwater Levels 203

	Page
Surface Drainage	203
Settlement	204
PROVISIONS FOR FUTURE REMEDIAL TREATMENT	204
Foundation Access	204
Records	205
CHAPTER VII: CONCLUSIONS	206
PREDICTION	206
DETECTION	207
EVALUATION AND TREATMENT	209
REFERENCES	211

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

Units of measurement in this report follow the usage of the original sources. Where U. S. Customary Units are used, they can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
feet per second	0.3048	metres per second
inches	0.0254	metres
pounds (mass)	0.45359237	kilograms
pounds (force)	4.448221615	newtons
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per sq foot	47.88026	pascals
pounds (force) per sq inch	6.894757×10^3	pascals

PREFACE

The study covered by this report was performed by the U. S. Army Engineer Waterways Experiment Station (WES) for the Nuclear Regulatory Commission (NRC) under Inter-Agency Agreement NRC-01-79-001, during the period 7 December 1978 to 31 March 1981. The Project Monitor for the NRC was Dr. Edward O'Donnell, of the Geosciences Standards Branch, Office of Standards Development. Chief of the Geosciences Standards Branch was Mr. Leon L. Beratan.

The report was prepared by Dr. A. G. Franklin, Mr. Dwain K. Butler, and Ms. Mary Ellen Hynes-Griffin of the Earthquake Engineering and Geophysics Division (EE&GD), Geotechnical Laboratory (GL); Dr. David Patrick and Mr. W. E. Strohm, Jr., of the Engineering Geology and Rock Mechanics Division (EG&RMD), GL. General supervision was provided by Dr. W. F. Marcuson, III, Acting Chief, EE&GD; Dr. Paul F. Hadala, Assistant Chief, GL; Dr. Don C. Banks, Chief, EG&RMD; and Mr. C. L. McAnear, Acting Chief, GL.

Commander and Director of WES was COL Nelson P. Conover, CE. Technical Director was Mr. F. R. Brown.

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CHAPTER I: INTRODUCTION

Where underground openings occur or are suspected at the site of a nuclear power plant or other important structure, it becomes necessary to evaluate the potential for ground collapse or subsidence that might be caused by such openings, and sometimes to devise remedial treatments. The geological and engineering problems involved are extremely demanding. However, they cannot always be avoided by choosing an alternative site in an area that is known to be above suspicion. Areas in which geological conditions or the activities of man can produce the potential for subsidence or collapse into underground openings cover a substantial portion of the continental United States.

Cavities or underground openings may occur as a result of solution activity in carbonate rocks or other soluble rocks; as caves in volcanic lavas; through mechanical erosion in weakly indurated sedimentary rocks; or as man-made excavations, most commonly underground mines, which may be poorly mapped, unmapped, or even unrecorded and forgotten. To some degree, resulting problems of exploration, problems of structural support, and engineering solutions to those problems are interchangeable, although the morphology of the openings and associated features may be very different.

The purpose of this report is to review pertinent current knowledge that will be of assistance in dealing with potential ground collapse or subsidence that could affect the safety of foundations or the performance of water-retaining structures at the sites of nuclear facilities. The material is, of course, also applicable to many other kinds of important projects. The basic issues involved may be characterized as: (a) prediction, (b) detection, (c) evaluation of the hazard, and (d) treatment.

Prediction involves a determination that the geological conditions at the site are or are not such that a potential for ground collapse may exist. Involved in this determination are questions of what conditions of geology, hydrology, climate, and cultural activity may be associated with the development of underground openings and possible ground collapse, and what geographical areas have been found to be susceptible to ground collapse. These questions are discussed in Chapter II of this report.

During the exploration of the site and the construction of the facility, it is essential that any cavities that could affect the safety of the structure be detected and sufficiently well defined and located so that appropriate remedial measures can be applied. Methods of site exploration, and particularly their applicability to the detection and definition of underground openings, are discussed in Chapters III and IV. Particular emphasis is given in this report to two areas within the larger topic of site exploration, because both have seen intensive developmental effort in recent years, have particular applicability to the investigation of possible underground openings, and appear to be on the threshold of attaining greatly increased importance in site investigations for important projects. These are geophysical methods of exploration and probabilistic considerations in planning site investigations. Chapter IV is devoted to geophysical methods of exploration, while other methods have been grouped in Chapter III under the heading of "Conventional Methods." The discussion of probabilistic considerations is applicable, in the present state of development, primarily to the use of borings, and so is included in Chapter III.

Evaluation of the hazard involves the identification of failure mechanisms, the likelihood of failure under various conditions, and the way in which such parameters as the size, number, and depths of underground openings affect the likelihood of failure. Also, a decision must be made as to whether existing conditions are amenable to remedial measures. These questions are discussed in Chapter V. Treatment of unsatisfactory foundations by means of engineering remedies such as backfilling or grouting is discussed in Chapter VI.

As mentioned in the preceeding paragraphs, the subject matter of this study is foundation safety on sites that may have subsurface cavities, a topic which is taken to include the integrity and proper functioning of foundations and water-retaining structures, engineering measures to deal with cavities (and associated conditions), and investigations to develop the requisite geological and engineering information for those purposes. Other diverse issues, some of great importance, are connected with land use on such terrains, especially karst terrains. Such issues are excluded from consideration in this report on the ground that its scope must have finite bounds. Among the excluded issues are questions of ecology, water supply, water quality, and other questions of hydrology that do not bear on foundation safety as defined above. Also excluded are problems of subsidence resulting from causes unrelated to cavities, such as consolidation of soft soils or withdrawal of oil or water from porous reservoirs.

CHAPTER II: THE ORIGINS OF UNDERGROUND OPENINGS

THE KARST ENVIRONMENT

Definition

The term _karst_ is a Germanized form of the Slovene word _Kras_ and the Italian word _carso_, both indicating bare, stony ground. _Karst_ signifies a terrain of limestone, dolomite, or gypsum, with a type of topography that is formed by dissolving or solution, and that is characterized by closed surface depressions or sinkholes, caves, and underground drainage (American Geological Institute, 1974). Areas of karst topography possess a unique overall environmental character in terms of surface morphology, lithology, underground openings, and surface and subsurface hydrology. These elements are critical to exploration and to the analysis and design of structures.

Morphology

Areas of karst exhibit characteristic surface and subsurface morphological features which may be indicative of potentially unstable sites. The terminology for these features is complex and definitions exist for a myriad of forms. A simplified terminology (U. S. Geological Survey, 1970a) for surface and subsurface morphological forms is given below.

Surface morphology

Probably the most characteristic surface form is the roughly circular, closed depression. Such features are called _sinks_, or _sinkholes_, or _dolines_. The outlet (if present) at the base of a sinkhole or a conduit leading downward is called a _swallow hole_ or _ponor_. Sinkholes that are partially filled with clay or rock rubble are called _filled sinkholes_. Although all karst sinkholes are ultimately caused by solution, some are produced by the solution and collapse of roofs of underground openings. The latter feature is called a _collapse sinkhole_ (and can occur in association with mined openings) whereas a sinkhole produced by solution alone is a solution sinkhole. A large depression formed by the coalescence of several sinkholes is a uvala. Figure 2.1 is a topographic map showing a sink-dominated landscape in Kentucky. Collapse sinks are often filled with coarse, angular rock fragments called breccia or collapse breccia. Solution sinks are usually filled with fine-grained material. The residual soils developed over limestone in some karst areas are relatively fine-grained and reddish in color; these soils are termed terra rossa. This material often lines the sides of unfilled solution sinks and occurs as fill material in filled sinks. Terra rossa soils are not universally present in karst areas, however.

Sinks whose bottom outlets have been plugged by these fine-grained soils will fill with water, forming karst ponds or karst lakes. These lakes or ponds may be ephemeral and drain periodically when the plugging material is eroded out.

Aside from the topographic irregularities due to the presence of sinks, the overall topography of some karst areas may be quite flat. Such areas are called karst plains and generally occur in regions of flat-lying rock. However, not all regions of flat-lying rock produce karst plains. A hummocky topography may also occur, particularly in tropical areas. The relief in karst areas is a function of climate, lithology, stratigraphy, geologic structure, and stage of karst development. For a more comprehensive treatment, see Sweeting (1973).

A karst environment may be either relatively modern, that is, formed during geologically recent (Holocene) or at most, Quaternary time, or it may be ancient, in which case it is called paleokarst.

Subsurface features

The most familiar subsurface features found in karst areas are caves and caverns. As with sinkholes, these features involve both solution and collapse. Generally, underground openings to be classed as caves

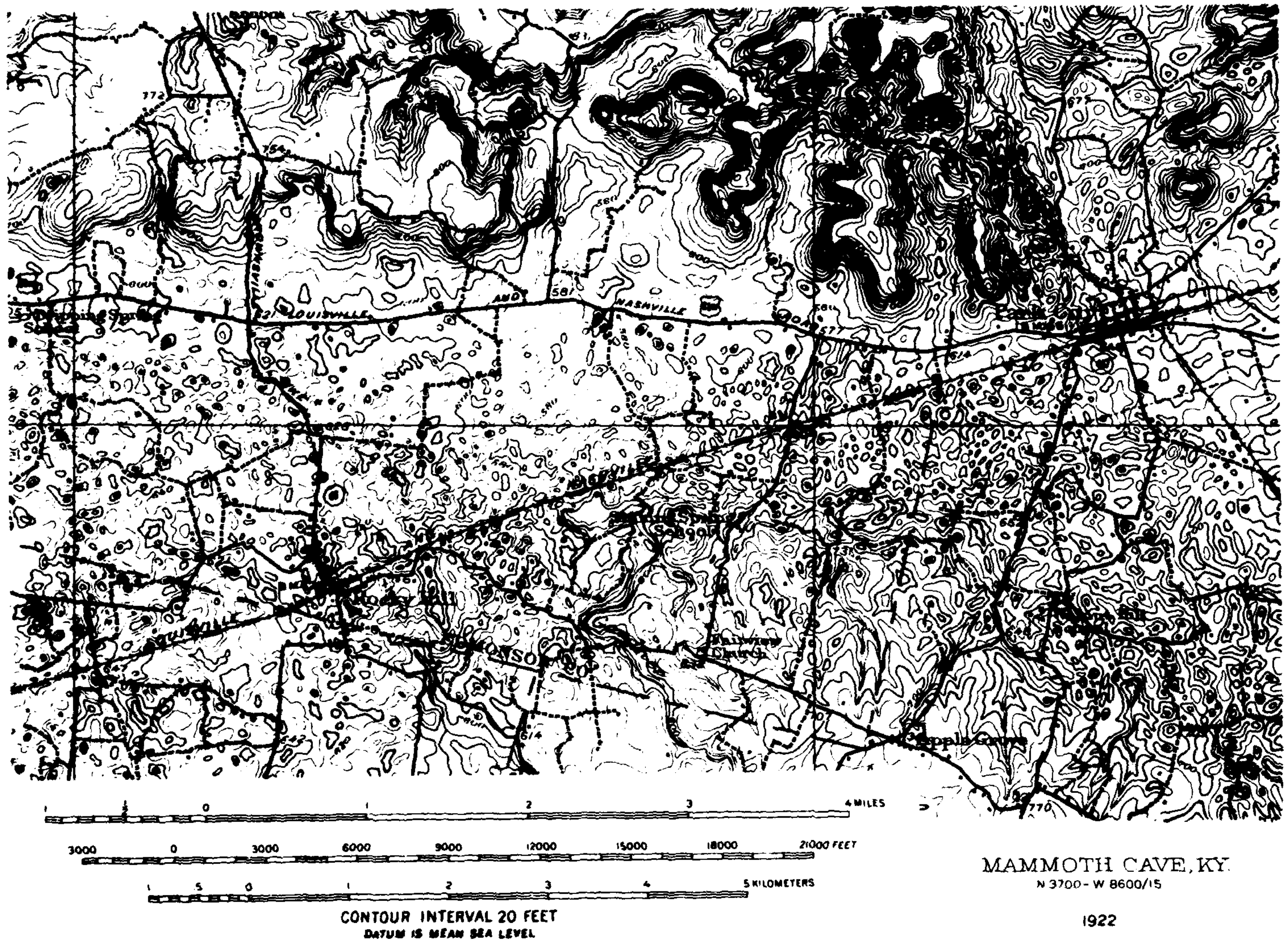

Figure 2.1. Topographic map of a sink-dominated landscape
(U. S. Geological Survey map)

must be of natural origin and must be of such size that a person can enter the opening. Caverns are considered caves of larger-than-average size. However, underground openings larger than pores occur in a range of sizes from small vugs measured in millimetres to large caverns measured in tens of metres. Also, underground openings smaller than caves as defined above may be of engineering significance. As will be seen in later paragraphs, solution may occur along joints and bedding planes, producing openings which may be quite extensive but yet not of sufficient dimension to permit access. In view of possible confusion attendant to the use of the term cave, it is recommended that the term cavity be used as a general term for all underground openings, whether natural or man-made, larger than a few millimetres. Linear or elongate cavities that are vertical are called joint cavities, grikes, or solution joints, and those that more or less follow bedding planes are called bedding-plane cavities.

Underground openings may have variable dimensions and exhibit either extremely simple or extremely complex geometry. The possibility that a particular karst area may exhibit a complex, three-dimensional network of underground openings makes site exploration more critical and more complicated than that conducted in nonkarst areas. Usually the degree of complexity is a function of geologic structure, discontinuity characteristics, and geomorphic history. Some understanding of the impact of these three factors may permit the estimation of the degree of complexity of cavern patterns in a given area. However, even having this understanding may not permit adequate prediction of caves and solution features in some areas.

Other features

Certain other morphological features characterize karst terrain but may not necessarily be classed as surface or subsurface. Of particular importance in limestone terrains is the relation between the residual soil and the parent rock, and the nature of the bedrock surface.

The thickness of residual soil (terra rossa or other types) lying above the parent limestone may be quite variable both locally, at a given site, and geographically. This natural variability precludes hard-and-fast rules for estimating soil thickness. Even so, there are several factors that may permit qualified estimation of thickness; these factors, which will be discussed in later sections, are (a) the nature of the limestone, (b) climate, and (c) stage of karst formation. Related to the variability of soil thickness is the irregularity of the bedrock surface at given sites. The irregularity and unpredictability of the surface is caused, in part, by differential solubility of the limestone, and may require a significantly greater exploration effort to define top of rock than in nonsoluble rock. Figure 2.2 illustrates an irregular limestone surface exposed in a quarry. The solutional openings are joint controlled. Another significant characteristic of the soil-rock interface is the abrupt nongradational transition from soil to rock; that is, there is often an absence of a well-defined zone of weathered rock. However, this lack of transition may be deceptive during drilling. Often, apparently sound rock may be succeeded by variable thicknesses of soil alternating with sound rock to considerable depth.

In glaciated areas, residual soils may be absent altogether; in the northern United States, glacial drift covering karst areas is common. Many examples of collapse features in glaciated karst are seen, e.g., in Minnesota and Michigan. Such features may on occasion be mistaken for kettles.

Differential solution may produce groove-, furrow-, or channel-shaped depressions on limestone surfaces. These may be exposed at the surface or may be covered by terra rossa soils. These depressions are often elongate and may be somewhat regular in appearance, and are superimposed upon the otherwise irregular limestone surface. The depths of these channels range from a few millimetres to more than a metre. These differential solution features are called <u>karren</u> or <u>lapies</u>. An example of irregular lapies in Indiana is shown in Figure 2.3.

Origin and Classification of Soluble Rocks

Soluble rocks, for the purpose of this report, include those sedimentary rocks that are appreciably soluble in water or weakly acidic solutions. Such rocks include carbonate types, chiefly limestones and

Figure 2.2. Terra Rossa resting on limestone in which are solution-enlarged joint openings. (Thornbury, 1969.)

Figure 2.3. Lapies near Mitchell, Indiana. (Thornbury, 1969.)

dolomites, and evaporites, of which halite, gypsum, and anhydrite are the most common.

Carbonate rocks

These rocks comprise approximately 22 percent of the stratigraphic column in the United States, and for the most part reflect deposition in shallow-water marine environments. Whereas limestones consist predominantly of calcite, or uncommonly the polymorph aragonite, with minor dolomite, quartz, feldspar, etc., the rock dolomite consists predominantly of the mineral dolomite with subordinate amounts of calcite, quartz, etc. The origin of dolomite is the subject of some controversy, but it is probable that most dolomite originates from the diagenetic alteration and recrystallization of limestone. Consistent with such a mode of origin is the observation that dolomite is more common in geologically older stratigraphic sections. Limestones consist of four distinct components: (a) Allochems. This principal component includes shells, shell fragments, and other organic detritus; oölites; intraclasts; and pellets of various kinds; all of which have originated within the basin of deposition. (b) Terrigenous grains. These are the subordinate, mostly noncarbonate clasts which have been derived from land and usually consist of quartz, feldspar, and clay minerals. (c) Orthochems. The orthochems are coarse-grained mineral cements, usually sparry calcite, which fill the void space between allochems and/or terrigenous grains; usually orthochems are precipitated authigenetically or during early diagenesis. (d) Micrite. This is microcrystalline, calcitic material of silt or clay size analogous to the terrigenous silt and clay matrix of sandstones. This material may fill void spaces between allochems. Generally void spaces are filled by either micrite or orthochems; combinations of these materials are not common. The allochems, orthochems, and micrite are susceptible to solution.

The classification of limestones is based upon the type of predominant allochem present and whether the void space is filled by orthochemical cement or by micrite. Thus, a rock consisting of predominant shell fragments cemented by sparry calcite cement would be roughly classed as a sparry, fossiliferous limestone, whereas a rock consisting mainly of pellets and micrite would be a micritic pellet limestone. For example, see the limestone classification of Folk (1974), given in Figure 2.4, and the relation between limestone classification and sandstone classification, shown in Figure 2.5.

Limestones may also be classified on the basis of the size of the predominant allochem according to the scheme below:

Gravel size - calcrudite
Sand size - calcarenite
Silt and/or clay size - calclutite

The noncarbonate and nonsoluble components of limestones mainly include chert, grains (clasts) of quartz, feldspar, and clay minerals. Generally, carbonate rocks that may present serious cavity problems contain only a few percent of these "insoluble" minerals. When the insoluble fraction approaches approximately 20 to 30 percent of the total rock, the soluble character of the rock may become significantly less pronounced. Hybrid rocks containing subequal amounts of carbonate and insolubles are generally less common than end-member types consisting of predominantly carbonate components (limestones) or insoluble components (shales and sandstones).

Evaporites

Although evaporites constitute approximately 3 percent of the stratigraphic column in the United States, solution problems in these materials may be locally of great importance. Gypsum, anhydrite, and rock salt (halite) are the more common rock types. Rock salt, although highly soluble, is of lesser interest because under natural conditions it dissolves mainly when it is exposed at the surface. This material usually is so impermeable that it does not permit groundwater movement, thus cavities are less common. However, if water is artificially introduced into a salt bed or dome, much solution may occur quickly. Gypsiferous rocks and anhydrite exhibit solution morphology similar to that of limestones and most of the discussion of solution phenomena pertaining to limestone also applies to gypsum.

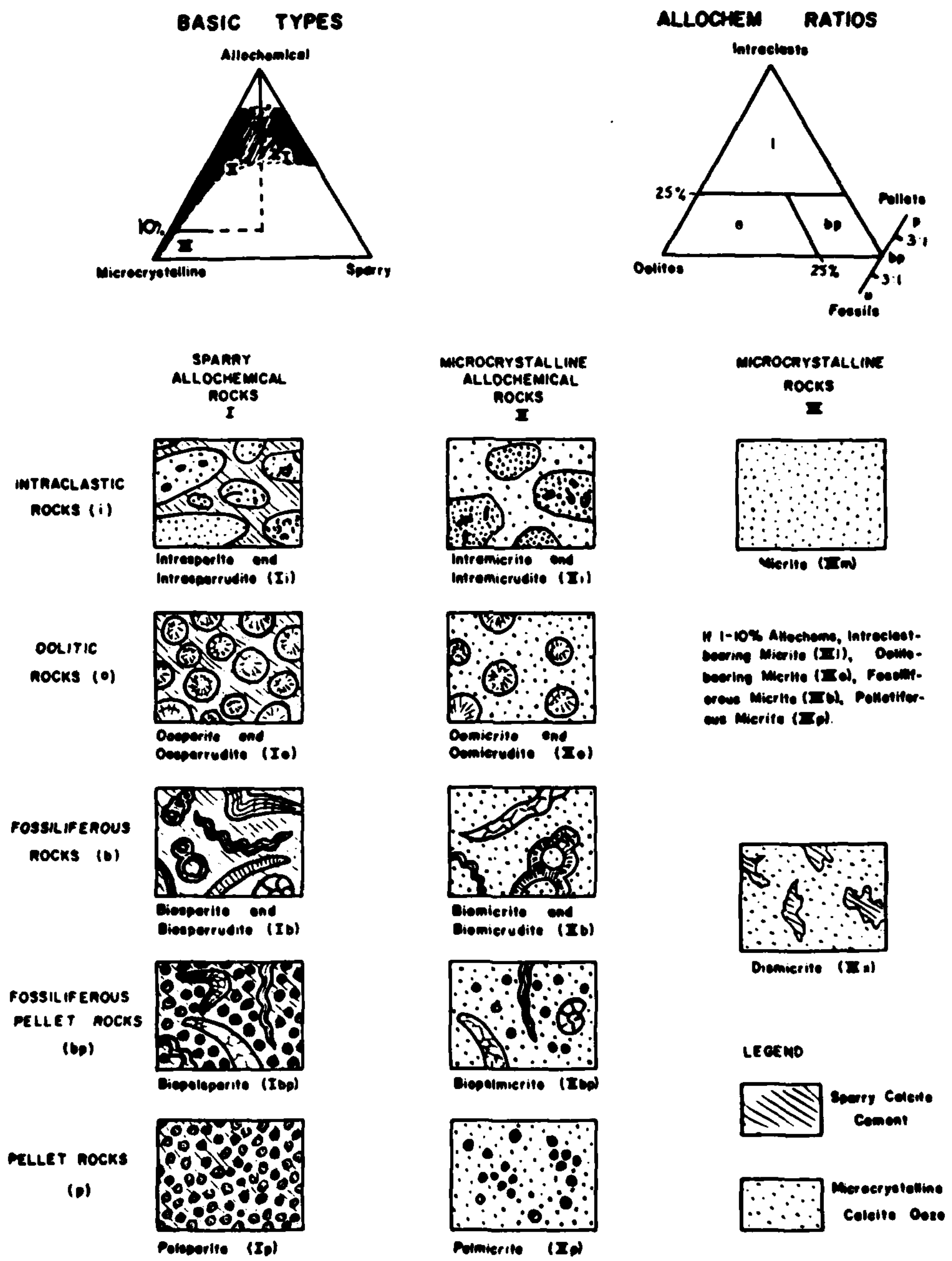

Figure 2.4. Compositional classification of limestones (Folk, 1974)

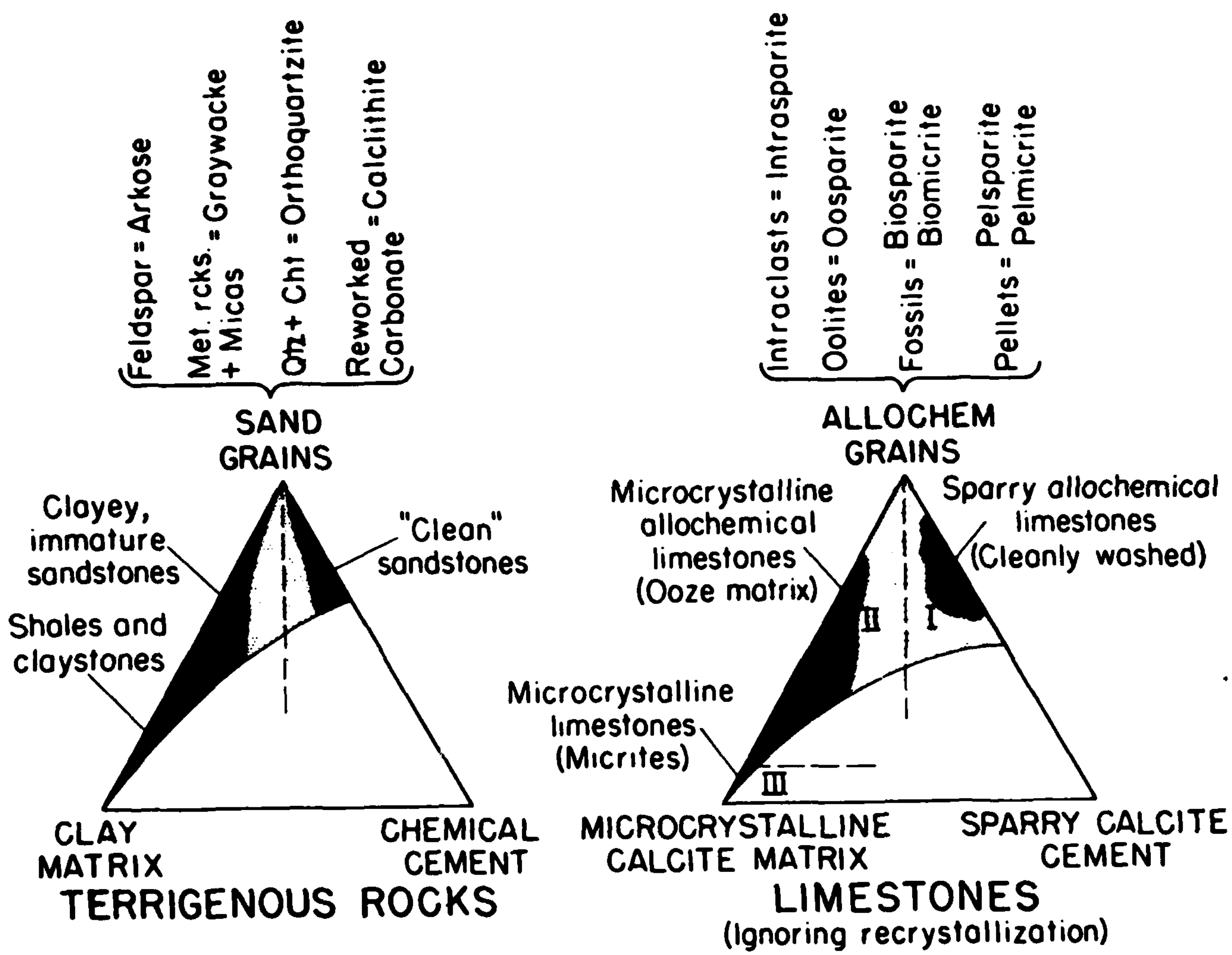

Figure 2.5. The relationship between limestone and sandstone classification (Folk, 1974)

Origin of Solution Features

Sinkholes, caves, and other solution features result from chemical solution operating with a complex interaction among mineralogic, lithologic, hydrologic, and geomorphic factors peculiar to a geographic area. Salient aspects of these interactions are given below.

Mineralogy and geochemistry

The constituents of carbonate rocks, namely calcite, aragonite, dolomite, and certain other less common minerals, are all to varying degrees soluble* in dilute, acidic solutions. The relative solubility of carbonate minerals in such solutions is shown below:

Dolomite	$Ca\ Mg\ (CO_3)_2$	↓ Increasing solubility
Calcite	$Ca\ CO_3$	
Aragonite	$Ca\ CO_3$	

Even though these carbonate minerals are considered "soluble," the actual magnitudes of their solubilities are low, as shown by the time required to produce karst landscapes. The acidic solutions occurring in surface and groundwater originate by the dissolving of atmospheric carbon dioxide (CO_2) gas in rainwater and by the addition of certain organic acids occurring in the soils to groundwater. The chemical equation for the dissolution of calcite in carbon dioxide-charged water is

$$CaCO_3 + CO_2 + H_2O \rightleftharpoons Ca(HCO_3)_2$$

---

* "Soluble" is a relative term. Most minerals break down to a greater or lesser degree in neutral water. The familiar abrasion pH as well as the hydrolysis reaction among silicate minerals are examples of forms of solution. Carbonate solution, however, usually results in complete ionic disassociation whereas hydrolysis results in crystalline products and disassociated ionic species.

However, the solubility of carbonate is somewhat more complex than this equation might imply. The complexity derives from the influence of three general factors: (a) temperature, (b) partial pressure of the CO_2 gas, and (c) the state of the CO_2. Generally carbonate solubility increases with decreasing temperature and increasing pressure. The rate of erosion through the operation of the chemical reactions described above will be accelerated under conditions of high hydraulic head and concentrated flow. Therefore, geomorphic conditions that result in steep hydraulic gradients and rock mass conditions that concentrate flows along discontinuities would tend to maximize solution potential. Acids resulting from man's activities, such as acid mine wastes and "acid rain" produced by burning fossil fuels, may cause some acceleration of carbonate dissolution. These causes probably are not significant factors affecting the time scale of cavity development. However, very little is known in quantitative terms about these effects.

The geochemical solution and weathering of evaporite deposits such as gypsum and halite may proceed much more quickly than that of the carbonate minerals, since the evaporites are more soluble. Thus, whereas quantitatively significant carbonate solution may require periods of geologic time (1,000's or 10,000's of years), evaporite solution of such magnitude may occur rapidly and during project life.

Weathering

The weathering of carbonate rocks and the formation of cavities are principally controlled by chemical solution, as described above. Chemical weathering proceeds at the upper surface of the rock above the water table. The dissolution of the carbonate components results in the residual accumulation of the insoluble quartz, feldspar, and clay minerals which compose the terra rossa soils mantling the surface of limestone terrains. The variability of solution rates with limestone composition may cause irregular bedrock surface and variable thicknesses of residual soil.

The movement of acidic waters from the surface vertically and horizontally along joints and bedding planes to the groundwater table results in the solution of the rock along these discontinuities. Such subsurface weathering produces cavities of variable size controlled by the orientation and nature of the discontinuity (fissure and bedding plane cavities). Caves, that is, larger and more equidimensional cavities, often are formed at the intersections of discontinuities. Generally the depth to which subsurface weathering and solution occurs is dependent upon the depth of the groundwater table or phreatic surface. The downward movement of soil water to the phreatic surface is influenced by the type of soil developed upon the limestone. Those carbonate rocks having appreciable chert will produce cherty soils exhibiting higher permeabilities than noncherty soil, which will enhance soil water movement and solution.

Geomorphology

The development of cavities or cavity systems in carbonate rocks is a complex phenomenon which generally requires long periods of time, measured in thousands of years. Also, the extent or characteristics of a given system is a reflection of the geomorphic history of the karst area in question. Those aspects of the geomorphic history that affect the character or extent of cavity development include climate and climatic change, and particularly, the evolution of the regional hydrologic environment. The groundwater regime generally exerts considerable control on the location and nature of cavities; thus, knowledge of former phreatic surfaces controlled or affected by changes in base level by Pleistocene sea level change may often be important.

Karst may be categorized on the basis of whether it has formed during quaternary time or in geologically ancient time, under conditions of erosion which were much different from those occurring today. The younger karst, which may have either active or inactive cavities, or both, as explained below, formed under conditions similar to those present today. The ancient karst is termed paleokarst. Buried karst is paleokarst that has been covered by younger sediments. When buried karst is exposed again at the surface by erosion, it is called exhumed karst.

Cavities may be considered to be either active or inactive. An active cave or cavity system is one in which the agencies that have produced it are still operating. However, a cavity system located a considerable distance above or below the present phreatic surface, for example, would usually be considered to be inactive. An active karst system in carbonate rocks would not necessarily be of greater hazard to engineering structures than an inactive system, at least with respect to solution, because of the extremely slow rates of carbonate solution. Those geomorphic processes that are important because of their swift and sudden occurrence are the expansion and development of sinkholes due either to removal of sinkhole filling materials or the collapse of cavities.

There is some doubt whether karst landscapes (or even other types) actually undergo a cycle of evolution; that is, a development that proceeds through stages beginning with youthful forms which, with the passage of time, will be followed by mature and ultimately old age forms. The process would be cyclic if baselevel or climatic changes occurred. A rather generalized concept of a karst cycle with three stages of evolution is illustrated by the four diagrams in Figure 2.6 (Strahler, 1960).

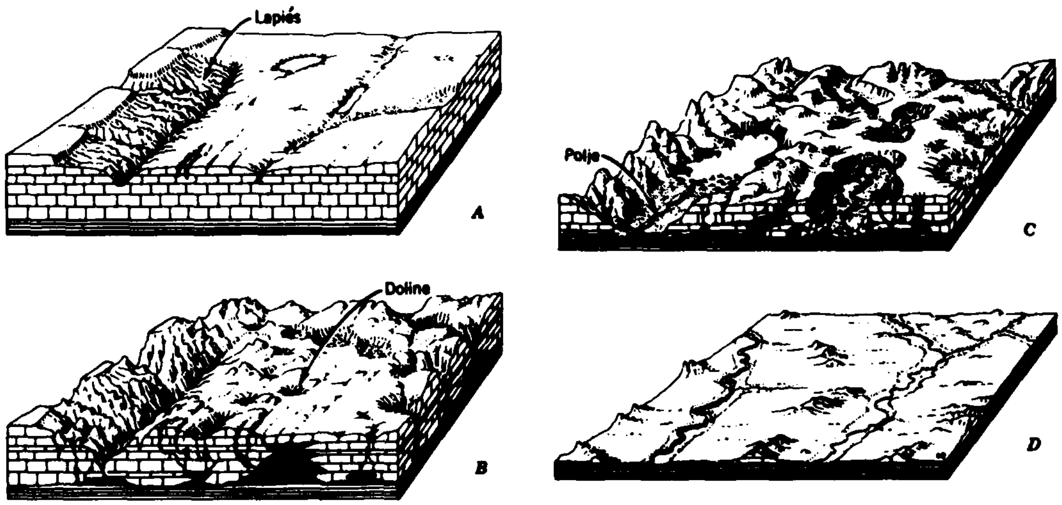

Figure 2.6. Evolution of a karst landscape (Strahler, 1960.) Copyright, John Wiley & Sons, Inc. Reprinted by permission.

Youth. In this stage, surface runoff is the most important form of drainage. Sinkholes are present, but underground drainage is not extensive, and no large caverns are present (A).

Maturity. During the mature stage, sinkholes are extensively developed, surface streams are rare or absent, and underground drainage through complex cavern systems is highly developed (B).

Old age. In this stage, surface drainage is becoming more important, collapse sinks are numerous and form windows, natural bridges are present, and circular limestone hills may be present (C). In an ideal cycle, the process would continue until essentially all of the soluble material was removed (D).

An example of the application of the concept of cyclic evolution to tropical karst is given by Jakucs (1976), who divides the sequence of evolution into four stages of development. During the first stage (I), surface drainage predominates and soils are eroded off the upland area and deposited in low areas. The concentration of soil and organic material in low areas accelerates solution there due to the higher concentration of acids, thus the lower areas are lowered even further. In the next stage (II), there exists considerable difference between rates and processes of weathering at the high and low areas. The removal of soil cover from the high areas generally protects them, resulting in the high areas remaining as nearly isolated hills (Stage III). These hills are called mogotes or pepinos. With increased solution many of the mogotes will be eroded as baselevel is approached and surface drainage again becomes significant. The remaining hills are referred to as karst inselbergs (Stage IV).

Cave Deposits

Although some cavities lack appreciable deposits of infilling material, many cavities contain extensive sedimentary deposits which affect the movement of water and the overall stability of the cavern. These materials may be classed as either detrital or chemical deposits and are described below.

Chemical deposits

These include the familiar stalagmites, stalactites, "cave flowers," and tufa, which have been chemically precipitated by slow-moving cave waters. These materials are usually calcareous but sometimes are gypsiferous. Generally, these forms are more important esthetically than for their effect on stability; however, occasionally chemical precipitates will cement detrital debris as well as form columns by the merging of stalagmites and stalactites.

Detrital deposits

Detrital or clastic deposits may be quite extensive in some cavities. These deposits consist of two general classes: material deposited by running water and fallen material from the roof. The particle sizes of these materials are variable and range from fine clay or colloid size up to boulders measured in metres. Usually, the finer materials have been deposited by water, whereas larger fragments have been derived from the walls and roofs of the cavern. Accumulations of coarse, blocky material of this kind are called cave breccia or breakdown. An accumulation of cave breccia in Wyandotte Cave, Indiana, is shown in Figure 2.7. Generally, the clays, silts, and sand deposited along and by underground watercourses have originated outside of the cavern system and possibly beyond the karst area. These sediments have originated from the subaerial weathering of the limestone bedrock and the erosion of residual limestone soils. These soils have been transported down joint systems or sinkholes and have been redeposited within the cavern system. Distinguishing between transported sediments filling a preexisting cavity and in-place, residual soil may not be easy. This results from the common occurrence of weathered rock beneath the ground surface, particularly along joint and bedding planes. Usually the coarse cave deposits, such as the breccia indicated above, have originated locally from the cavern wall or roof; however, some such material may also originate on the surface and be subsequently transported into the cave system. The locally derived material results from the collapse or failure of roof material due to the gradual enlargement of the cavity. Often these

Figure 2.7. Cave breccia in Wyandotte Cave, Indiana (Thornbury, 1969.)
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failures are concentrated in cavities beneath sinkholes. The roof collapse is similar to stoping and may extend upward into nonsoluble rock. Generally, the roof debris will accumulate on the cave floor below, where it may be interbedded with fine-grained material and where it may be cemented into a rock-like mass. In some caves, accumulations of chemical and detrital deposits have essentially filled the cavity.

Pseudokarst

Pseudokarst is a term applied to surface forms (sinkholes) and subsurface forms (cavities) that occur in nonsoluble earth materials but are similar to features found in limestone or gypsum terrains. The similarity is mainly morphological and usually does not involve the hydrologic complexities of karst. Examples of pseudokarst in terms of surface and subsurface features are given below.

Surface forms

Sinkhole-like depressions are found in periglacial regions, in loessial soils, in certain sands and gravels, and in coarse-grained intrusive igneous rocks. Periglacial sinkholes (kettles) result from the melting of buried ice lenses and the subsequent collapse of the overlying soil. Often loess (wind-deposited silt) and some sandy and gravelly soils possess a certain degree of calcium carbonate cementation which, upon dissolution of the cement, will produce surface depressions resembling karst sinkholes. These features probably owe their origin as much to erosion as to solution. Small sinkholes can also occur in granites, granodiorites, and similar rock. These features probably involve minimal solution accompanied by hydrolysis as well as other chemical weathering processes. Erosion and abrasion undoubtedly also play a role.

Subsurface forms

The most common example of caves not formed by solution are those associated with lava flows. Lava caves occur during extrusion of basalts and are caused by differences in cooling rates between the interior and margins of the flow. The margins will tend to cool more quickly, and thus crystallization will be initiated at the periphery before the interior, which is better insulated. The interior material will tend to flow further leaving an empty tube surrounded by the earlier crystallized exterior. These tubes, which may be spatially quite complex, are lava caves. Subsurface cavities may also occur in sedimentary rocks, particularly sandstones in which cements are minimal or absent. A common example of cavities developed in nonsoluble rocks is that of sea caves along coastlines, developed primarily due to mechanical erosion. At Minneapolis, Minnesota, several caves occur in the St. Peter sandstone as a result of piping in those very weakly indurated rocks. Some of these cavities extend for large distances back from the outcrop of the St. Peter formation in the gorge of the Mississippi River, reaching the area beneath the business district of Minneapolis (Hogberg and Bayer, 1967; Kress and Alexander, 1980; Spong, 1980).

Care must be taken to insure that pseudokarst is distinguished from true karst. The presence of sinkholes in a normally nonsoluble material may be an indication of pseudokarst, or it may be an indication that the nonsoluble material overlies limestone and that solution of the limestone has initiated sinkhole formation above by stoping.

FACTORS AFFECTING THE DEVELOPMENT AND POTENTIAL HAZARD OF SOLUTION FEATURES

The factors which contribute to or control the extent or magnitude of underground solution may be categorized as either geological or environmental. Geological factors include the nature and characterization of the rock and the rock mass; the environmental factors are those which operate upon the geological factors and include hydrology, seismicity, and climate.

Geological Factors

Rock properties

Mineralogy. Those rocks containing calcite, halite, gypsum, or anhydrite as the predominant mineral constituents will be the most susceptible to solution and the development of underground cavities.

Lithology. Purer carbonate, rock salt, or gypsiferous rock exhibiting minimal nonsoluble constituents such as quartz or clay minerals will be the more susceptible. Porosity and permeability may result from solution of either the allochemical or orthochemical constituents. Also, porosity may occur due to the incomplete cementation by the orthochemical cements. These contributions to porosity and permeability may not be as important as the porosity and permeability due to joints and other discontinuities in the rock mass, but the determination of lateral and vertical distribution of porosity may give some indication of the tightness of the carbonate, or soluble unit. The size and nature of the allochemical constituents and the amount of micrite present may control porosity and solution susceptibility. Coarse-grained, loosely packed shell or coral fragments and oölitic material, incompletely cemented and without appreciable micrite, would be considerably more porous than a rock composed of finer-grained, organic debris accompanied by micrite and terrigenous fines. Ordinarily, carbonate rocks with low porosity and permeability are most likely to form solution cavities, assuming of course, that discontinuities are present, because of the concentration of flow. In the absence of discontinuities, solution will occur by means of intergranular porosity and permeability, but this is less likely to produce cavities.

Diagenesis. Diagenetic alteration may either increase or decrease solution susceptibility by affecting porosity and permeability. The effects of diagenesis include introduction of allochemical cements, solution and/or recrystallization of allochemical constituents, and dolomitization, to name a few. Generally, carbonate rocks exhibit very complex diagenetic alterations. For example, in a few millimetres, a rock can exhibit incipient dolomitization, grain growth, and recrystallization of allochems, as well as diminution of grain size in orthochems. Although carbonate rocks that have been diagenetically altered to dolomite may have decreased susceptibility to solution, they may exhibit increased porosity and permeability. The chemical nature of diagenetic processes is very similar to that of weathering processes. Thus, it may be useful to determine whether observed rock alterations developed early in the history of the rock or have occurred during the current cycle of weathering and erosion. The latter would be of more significance as an indicator of potential solution problems.

Rock mass properties

Stratigraphy. The thickness, areal extent, facies relations, and presence or absence of nonsoluble interbeds may be valuable indications of the extent to which cavities may be present. Generally, the development of integrated cavity networks is enhanced in those stratigraphic units that are relatively thinly bedded, lack insoluble interbeds, and exhibit uniform, widespread occurrence (Thornbury, 1969). Wide regional occurrence of solution features would indicate the infrequency of occurrence of insoluble facies. However, insoluble interbeds may contribute to the formation of isolated cavities, which also may be important.* Carbonate rock units may exhibit rather complex facies relationships over short distances; for instance, reefs or shell banks consisting of rather coarse organic debris may grade laterally into fine-grained, low-energy, deep-water, micritic deposits. Generally, stratigraphic control of cavity formation is quite complex and not amenable to strict, hard, or fast rules.

Structure. Folding and faulting of potentially soluble rock units may affect cavern formation to the extent that these processes have modified the lithology of the original rock unit. Thus, the folding of certain carbonate rock units, together with other contributing factors (such as a source of magnesium ion), has resulted in a partial alteration of the original calcite to the less soluble dolomite. Probably of more

* Eberhard Werner, Personal Communication, 1980.

importance, however, is the effect of folding and faulting on the discontinuities as well as on the hydrologic regime. For example, folding may result in confined (artesian) flow conditions which may produce cavities at considerable depth. Folding can also affect the areal extent of soluble rock units by confining them to narrow belts along the strike of folds, while on the other hand, flat-lying, nonfolded units would have a much larger outcrop area.

Discontinuities. The presence of joints, faults, fracture zones, and bedding planes in soluble rocks is probably the single most important factor in the development of underground openings. Generally, the movement of water from the surface to the groundwater table, as well as movement beneath the groundwater table, occurs almost exclusively along discontinuities. The movements, particularly below the water table, may be quite tortuous and concentrate solution and cavity formation along discontinuities and at the intersections of discontinuities. The importance of discontinuities, particularly jointing, in cavity formation requires that the identification and mapping of joints and joint systems be given a high priority during exploration phases of project studies. Figures 2.8 and 2.9 illustrate the influence of structure and discontinuities on cavern location.

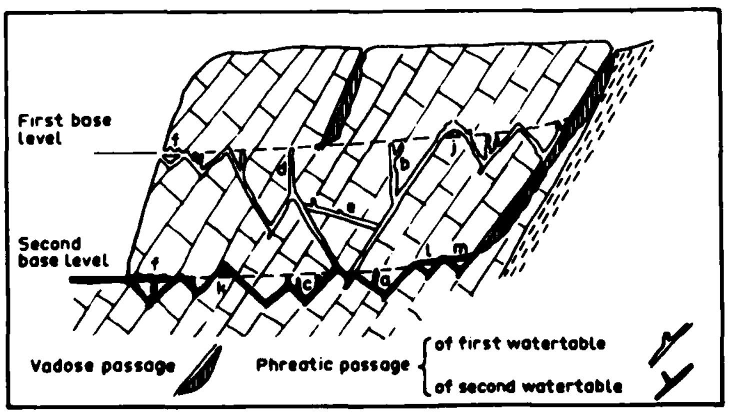


Figure 2.8. Influence of steeply dipping beds on development of Mendip Cave (Jennings, 1971)

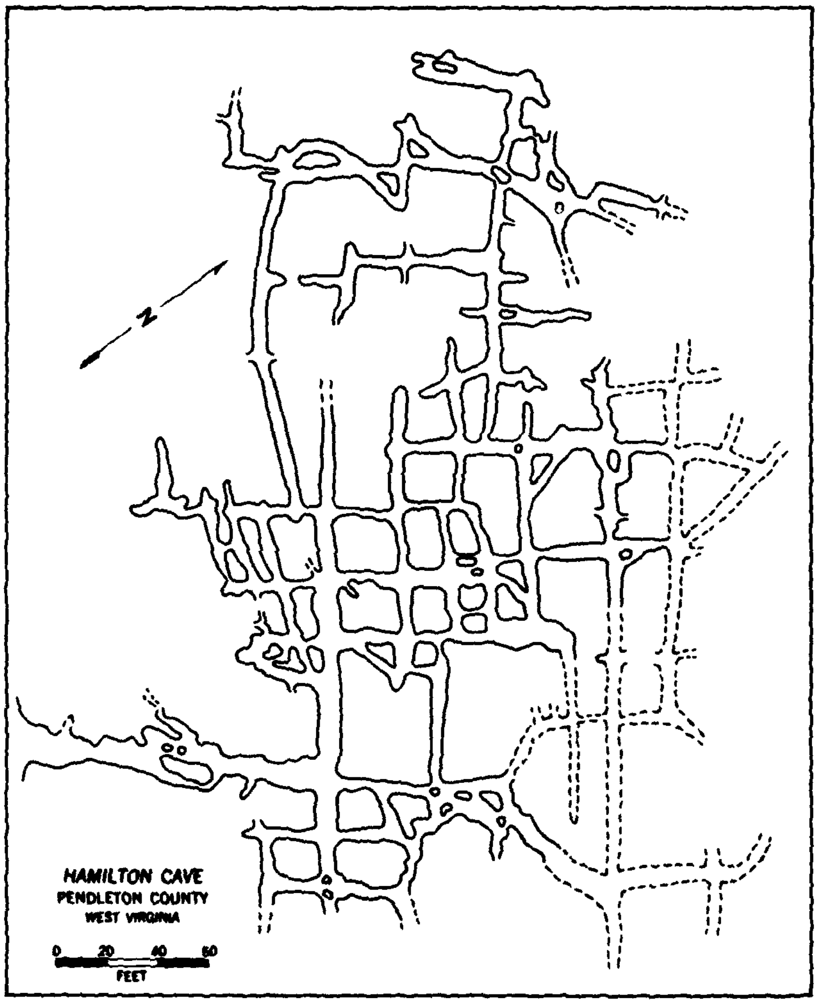


Figure 2.9. Plan of a cavern showing joint control. (Thornbury, 1969, after W. E. Davies, 1959.) Copyright, John Wiley & Sons, Inc. Reprinted by permission.

Strength. The shearing and compressive strengths of the rock mass (along with the geometry of the cavity) would control the extent to which an underground cavity would be susceptible to collapse. The rock mass strength is governed to some degree by the rock strength, but usually of more importance are the geometry and spacing of discontinuities, the frictional properties of the discontinuity surfaces, and the strengths of any infilling materials. Even so, the rock mass strength, as well as the rock strength, may be a function of the age and diagenetic history of the geologic unit; thus, the older Paleozoic carbonates would be expected to exhibit greater strengths than the Tertiary carbonates.

Environmental Factors

Surface hydrology

Both the surface and the subsurface hydrologic regimes of karst areas are critical elements in the development of caverns. An understanding of the hydrology may contribute to the understanding of the nature of caverns and the probable location and extent of underground openings.

In the elucidation of the possible extent of cavities in a particular area, it is necessary to consider not only the modern surface hydrologic regime but also the regime as it existed during previous periods of the Holocene and possibly Pleistocene times. For example, the absence of modern-day surface drainage in an area would be an obvious indication that subsurface flows were occurring and that extensive underground openings may exist. Also it may be possible to determine the relative amount of surface runoff carried by surface streams and thereby estimate the amount carried by subsurface flows. Since groundwater flow is more or less controlled by surface stream regimes which themselves define the local baselevel, the understanding of local baselevel changes caused, for example, by Pleistocene sea level changes, would suggest whether or not cavities could be expected at elevations above or below the modern water table surface. Baselevel changes may be evident from studies of stream terraces or other geomorphic features. The effects of baselevel changes on cavern location are shown in Figure 2.10, where the sequential decrease in baselevel through stages A to D show increased depth of cave formation. Figure 2.11 shows similar relations.

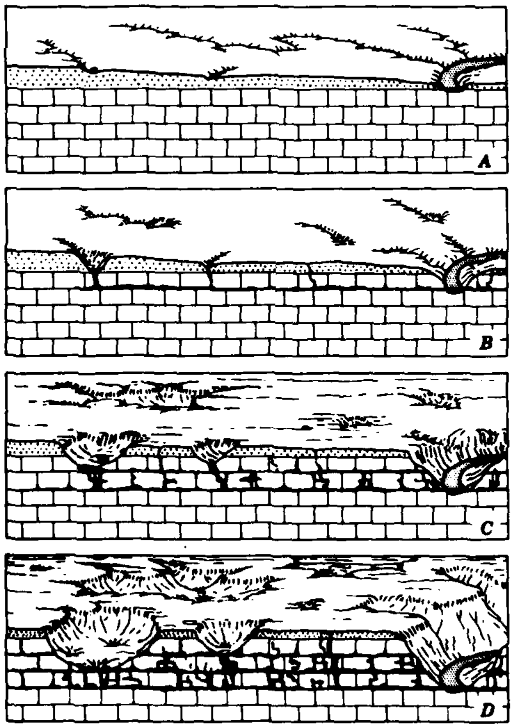


Figure 2.10. The influence of local baselevel on the location of cavern formation (Strahler, 1960.) Copyright, John Wiley & Sons, Inc. Reprinted by permission.

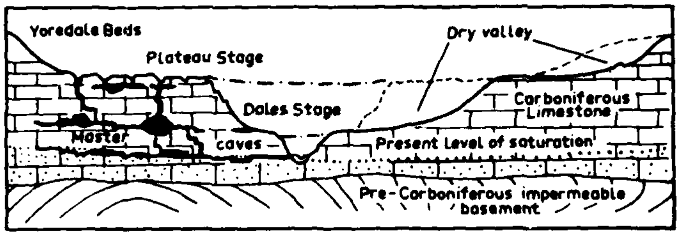


Figure 2.11. Karst evolution in Craven, England (Jennings, 1971)

Subsurface hydrology

The manner in which the groundwater table influences the development of cavities has been controversial in that theories have been proposed which require that caves form at, above, and below the water table. Generally, current studies indicate that caves form "near" the water table. However, as indicated in the previous paragraph, movement of the water table due to baselevel changes would indicate that caverns could exist considerably above or below the modern water table. Also, one must consider whether or not confined or artesian conditions are present; if they are, cavities could occur at considerable depth. Of more importance is the rate of groundwater movement through the joint and bedding plane system. Faster movement accelerates solution by bringing in supplies of acidic waters and by removing soluble residues. The rate of discharge is, in part, a function of the hydraulic gradient, since steeper gradients result in higher discharges. Thus, those areas in which surface streams have incised or entrenched deeply will exhibit well-developed karst in uplands along the stream valley.

Climate

The regional climate controls cavity formation by temperature effects on solution rates and weathering processes and by meteorological effects on ground- and surface-water levels. The results of these climatic influences are karst landforms peculiar to specific climates such as those of temperate, arid, and tropical environments. In general, high temperatures and high precipitation will greatly accelerate karst processes. Thus, carbonate rocks in true desert areas will not be subject to solution due to surface infiltration, whereas similar rocks in tropical areas may exhibit extensive solution. However, carbonate rocks underlying desert areas can be subjected to karst processes, if, for example, the rock unit is also a confined aquifer. Also, modern deserts may exhibit exhumed or relic karst features which have originated in an earlier, wetter period. Karst features in the U. S. may not be meaningfullly categorized on the basis of climate since they occur in more or less temperate conditions. The majority of the karst areas of the U. S. exhibit a range in mean annual precipitation (MAP) between approximately 32 in. (81.3 cm) and 56 in. (142.2 cm). The exception to this range is the Pecos Valley area of New Mexico and Texas where the MAP ranges between 8 in. (20.3 cm) and 16 in. (40.6 cm). Although dry, this area would not be classed as a true desert.

Although there are no examples of tropical karst in the continental U. S., this type does occur in Puerto Rico. Whereas temperate karst landforms usually exhibit rather flat or somewhat undulating surfaces, depending upon the extent of uvalas, tropical karst, particularly at certain stages of development, may exhibit considerable relief.

GEOGRAPHICAL DISTRIBUTION OF UNDERGROUND OPENINGS AND SOLUTION FEATURES IN THE UNITED STATES

Areal Distribution of Karst and Pseudokarst Features

As indicated previously, carbonate rocks comprise approximately 22 percent of the stratigraphic column in the United States, and it would be expected that these materials would also exhibit a large geographical area of occurrence. Approximately 15 percent of the continental U. S. has soluble materials at or near the surface (Herak and Stringfield, 1970). An appreciation of this areal extent may be obtained from an examination of Figure 2.12, which shows surface bedrock materials classed as limestone and/or dolomite, predominant limestone with sandstone, and predominant limestone with shale (Belcher et al., 1946). Note that this

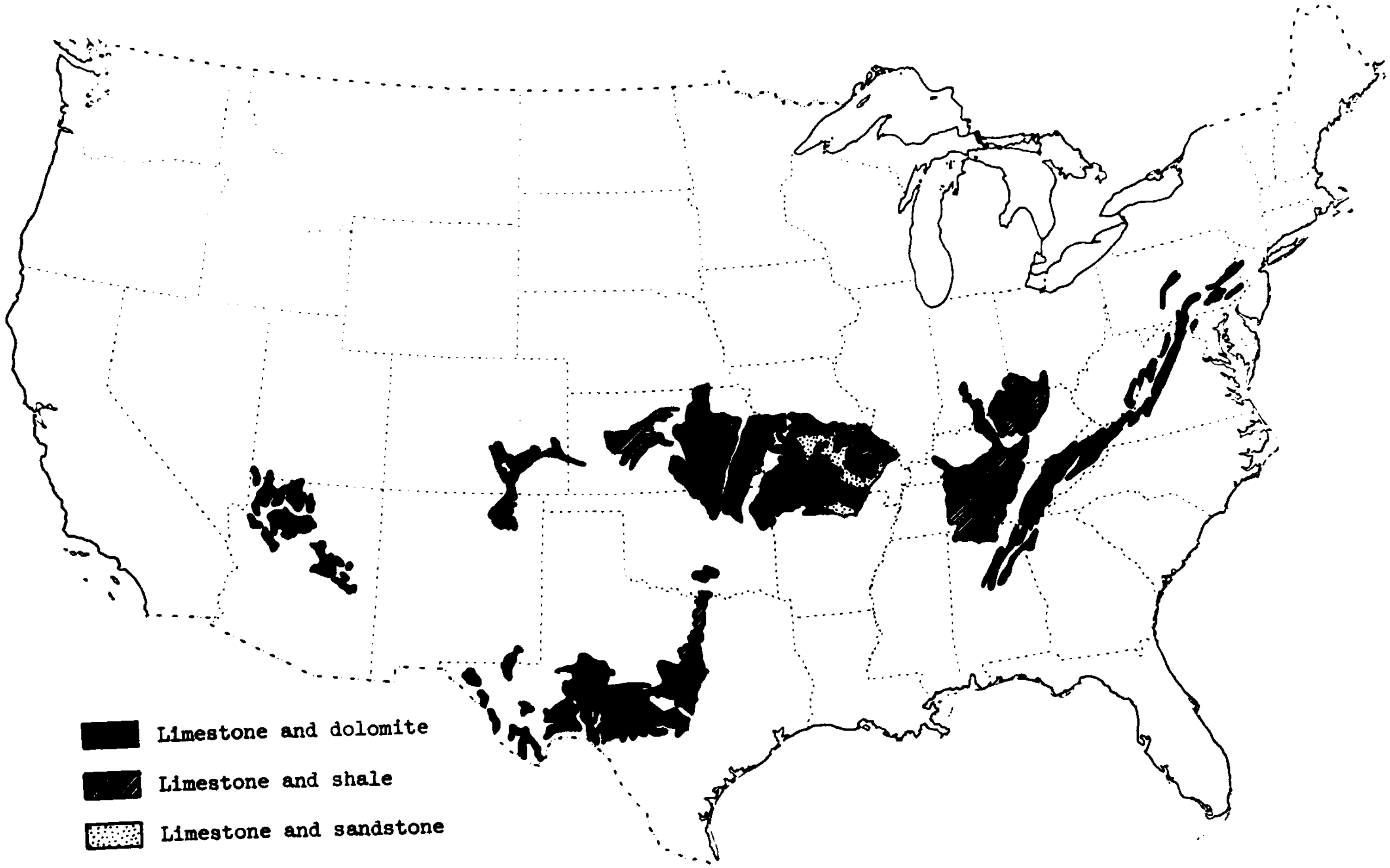


Figure 2.12. Major areas of limestone outcrops in the continental United States (After Belcher, et al, 1946)

map only shows areas in which limestone occur at the surface or underlie residual soils; thus, limestones underlying transported soils, such as those covered by glacial drift in the midwest or those under coastal plain sediments in Florida and along the Gulf Coast, are not included. Although one would suppose that those areas underlain by limestones and/or dolomites would be the most susceptible to solution, the map yields no definitive information on relative susceptibility. Figures 2.13 and 2.14, which are reproduced from the U. S. National Atlas, (U. S. Geological Survey, 1970b), provide some additional information. Figure 2.13 shows the distribution of surficial karst and pseudokarst features and Figure 2.14 shows the distribution of caverns developed under karst and pseudokarst processes. The originals of these maps use a color-coded classification of the various types of karst and pseudokarst features which cannot be shown in these black-and-white reproductions. These figures will serve, however, to indicate where such features have been observed and reported. There are several interesting differences between the limestone occurrence map (Figure 2.12) and the karst and pseudokarst maps. Note the extensive development of surficial karst in southern Alabama, Georgia, and South Carolina, and in parts of Florida; recall that these occurrences were not shown on the limestone occurrence map. Also note that the limestone occurrence map shows areas of rather extensive limestone areas in Kansas which do not exhibit extensive karst features. Most of these limestones occur interbedded with shales.

Figure 2.15 is a map prepared by W. E. Davies of the U. S. Geological Survey, which combines the data given in the previous maps. This map distinguishes between the occurrence of karst features and the occurrence of soluble materials; however, pseudokarst is not included.

The maps showing distributions of karst areas and potential or actual soluble materials are intended to demonstrate the wide distribution and variability of the areas and materials. The reader is cautioned not to rely upon such small-scale maps for detailed information. Furthermore, the presence or absence of karst is controlled in large part by other factors besides presence or absence of soluble rocks. In many cases

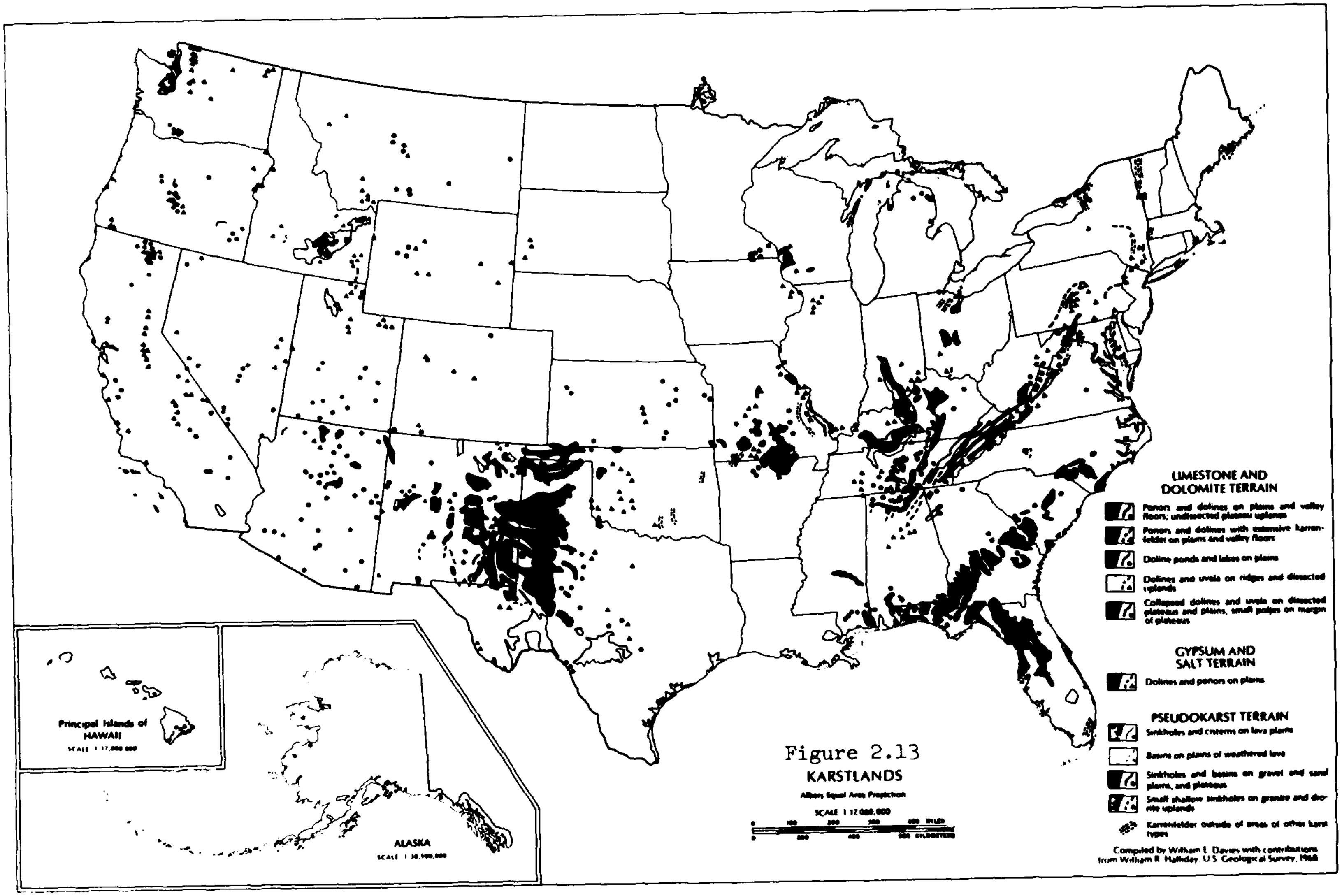


Figure 2.13
KARSTLANDS

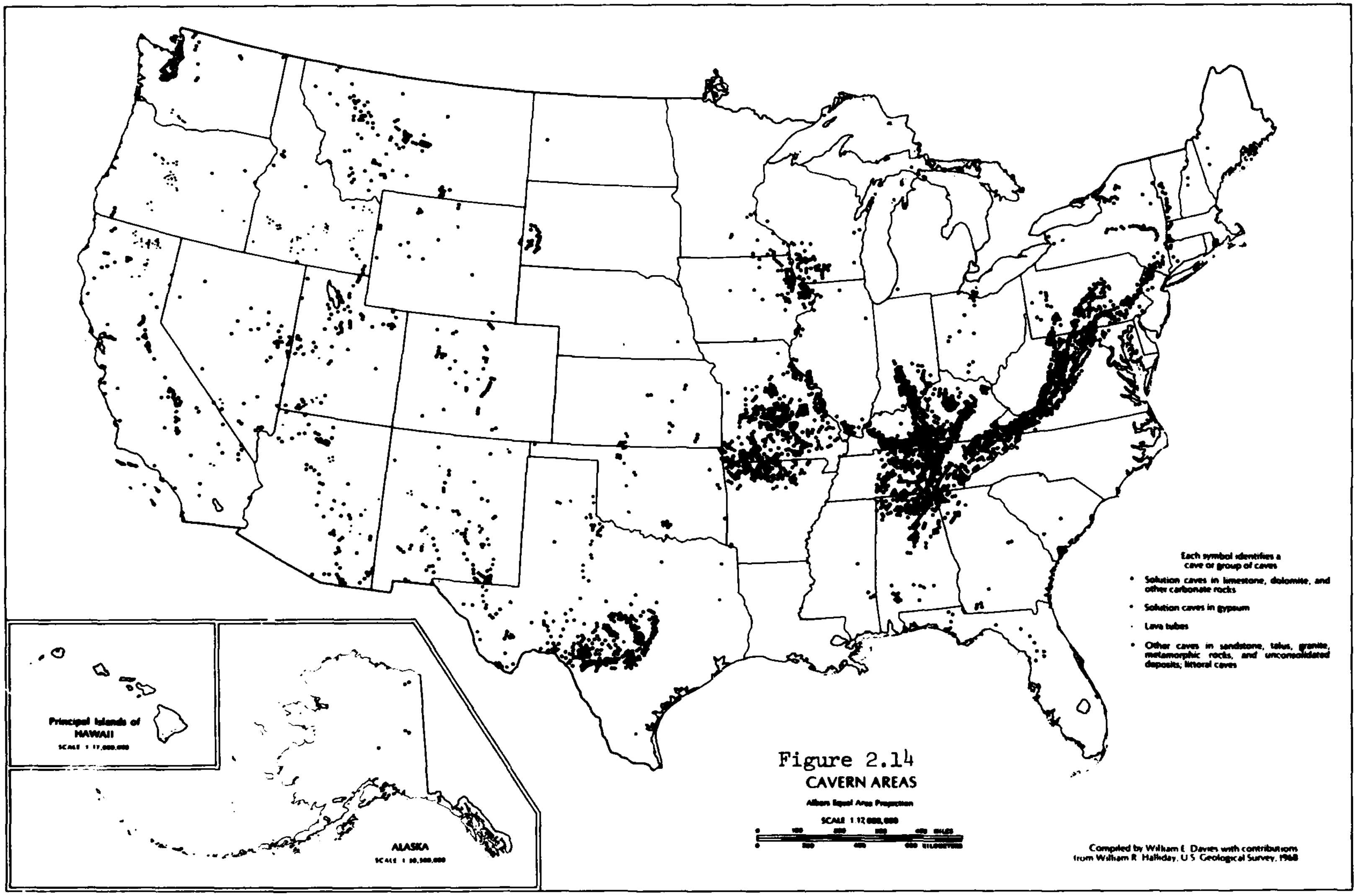


Figure 2.14
CAVERN AREAS

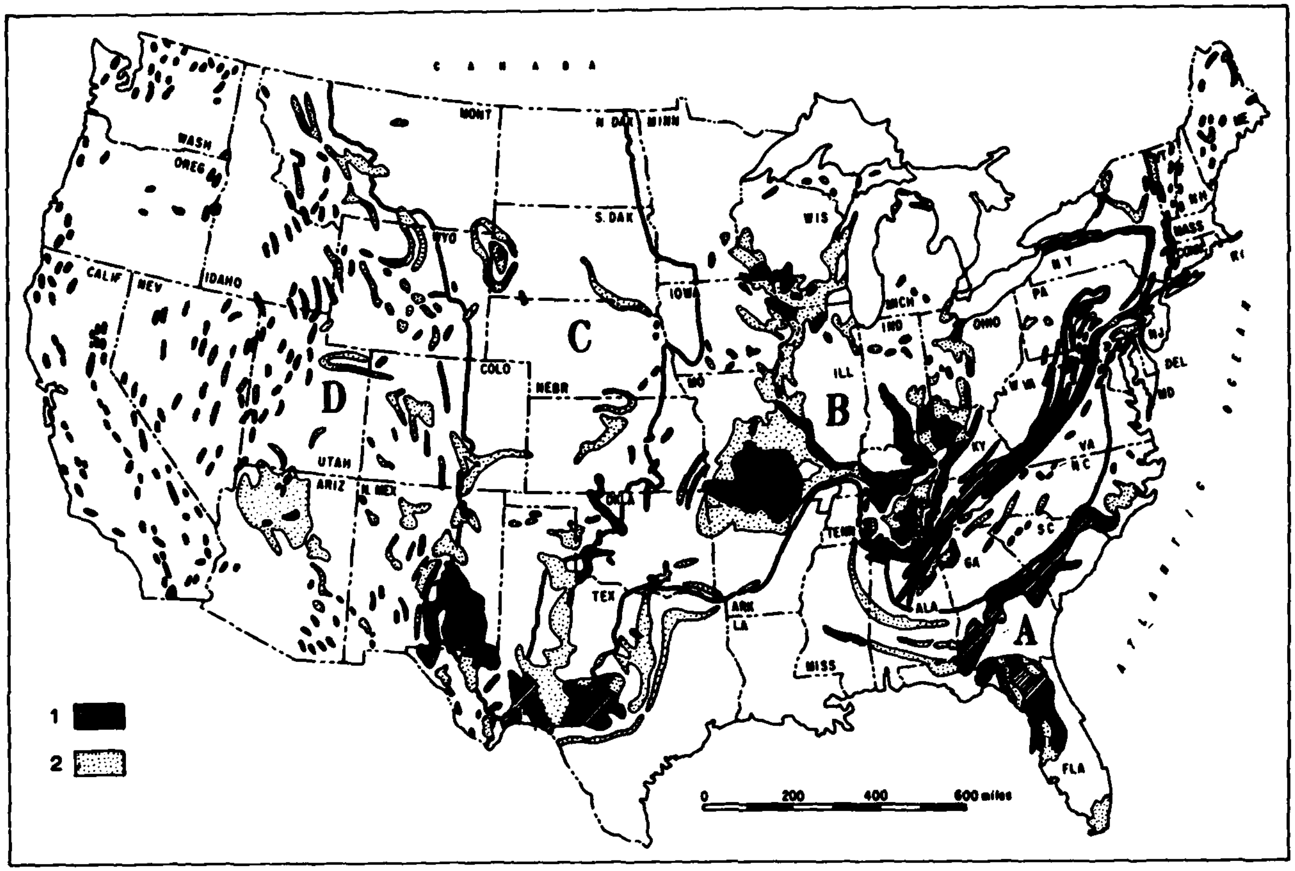


Figure 2.15. Distribution of karst areas in relation to carbonate and sulphate rocks in the U. S. A = Atlantic and Gulf Coastal Plain region; B = east-central region of Palaeozoic and other old rocks; C = Great Plains region; D = western mountain region; 1 = karst areas; 2 = carbonate and sulphate rocks at or near the surface. (By W. E. Davies, U. S. Geological Survey.)

more detailed, larger scale maps are available from state geological surveys and/or the USGS. Contact with these state or Federal agencies is highly recommended.

Summary by Physiographic Province

The categorization of some types of geologic hazards, such as troublesome engineering materials, earthquakes, vulcanism, and karst areas, in terms of physiographic provinces of occurrence is often a convenient procedure for describing the particular hazard or phenomenon. This results from the fact that most physiographic province boundaries are more or less based upon regional geologic structure and depositional patterns and the individual province often exhibits a relatively homogeneous climatic zone. Since karst features are, in part, controlled by geologic structure, lithology (controlled by depositional patterns) and climate, the karst features occurring in a particular province should have much in common. Figure 2.16 shows the first order physiographic provinces of the United States. Generally, those areas in which there is extensive development of karst or pseudokarst features include portions of the Newer Appalachians (No. 16) in Pennsylvania, Maryland, Virginia, Tennessee, and Alabama; the Appalachian Plateau (No. 15) from Pennsylvania to Alabama; the Interior Low Plateaus (No. 14) in Indiana, Kentucky, and Tennessee; the Ozark and Ouachita Plateaus (No. 13) in Missouri and Arkansas; the Atlantic and Gulf Coastal Plain (No. 20) in Georgia, Florida, and the Carolinas; and the Great Plains (No. 10) in New Mexico, Texas and Oklahoma (Herak and Stringfield, 1970).

Newer Appalachians

The Newer Appalachians, or Valley and Ridge Physiographic Province, particularly in that portion referred to as the Great Valley, exhibits extensive surface and subsurface karst features. Figure 2.17 shows areas of karst in the Newer Appalachian and Appalachian Plateau Provinces. Cavern and sinkhole development have occurred in steeply dipping Lower Paleozoic limestones and dolomites. These solution features, which cut

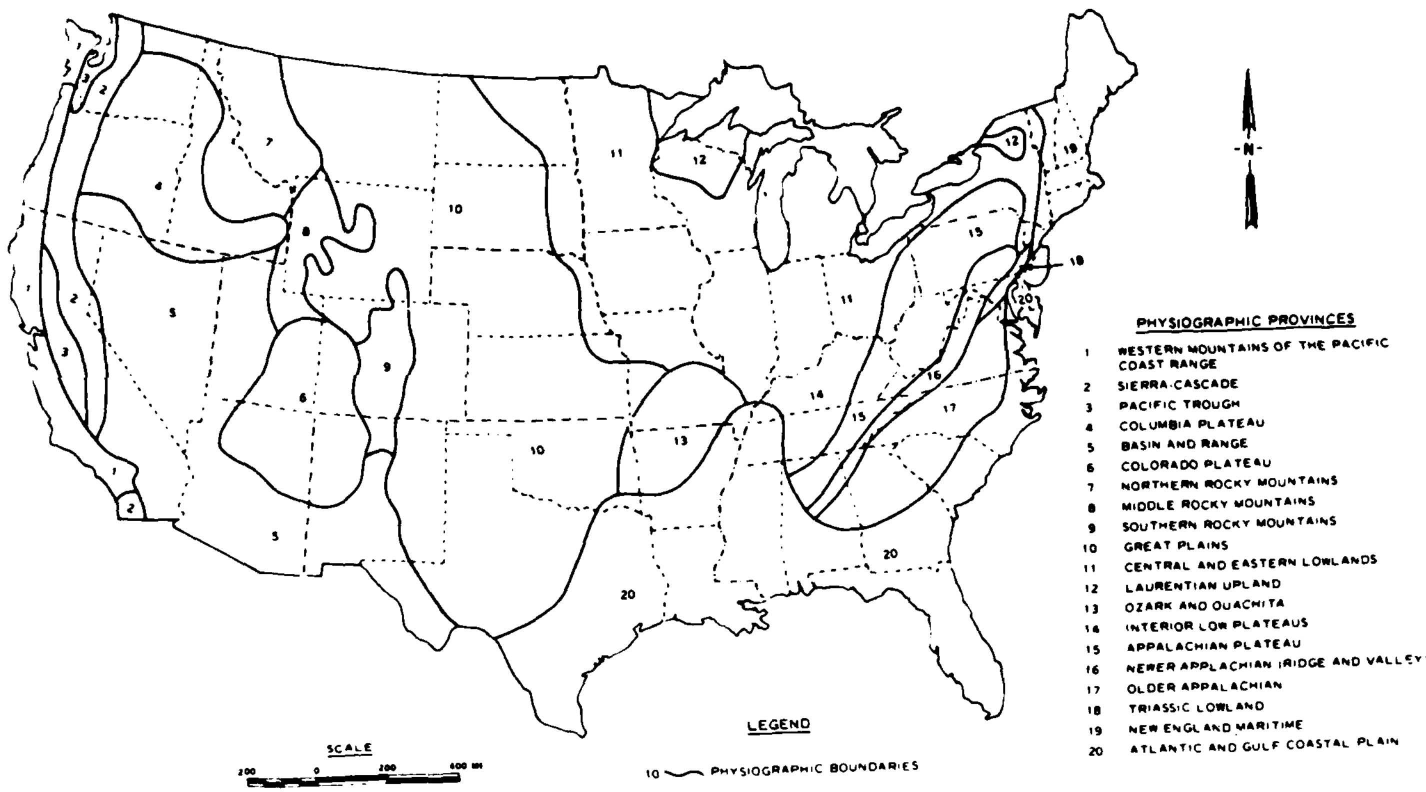


Figure 2.16. First order physiographic provinces within the continental United States (After Atwood, 1940)

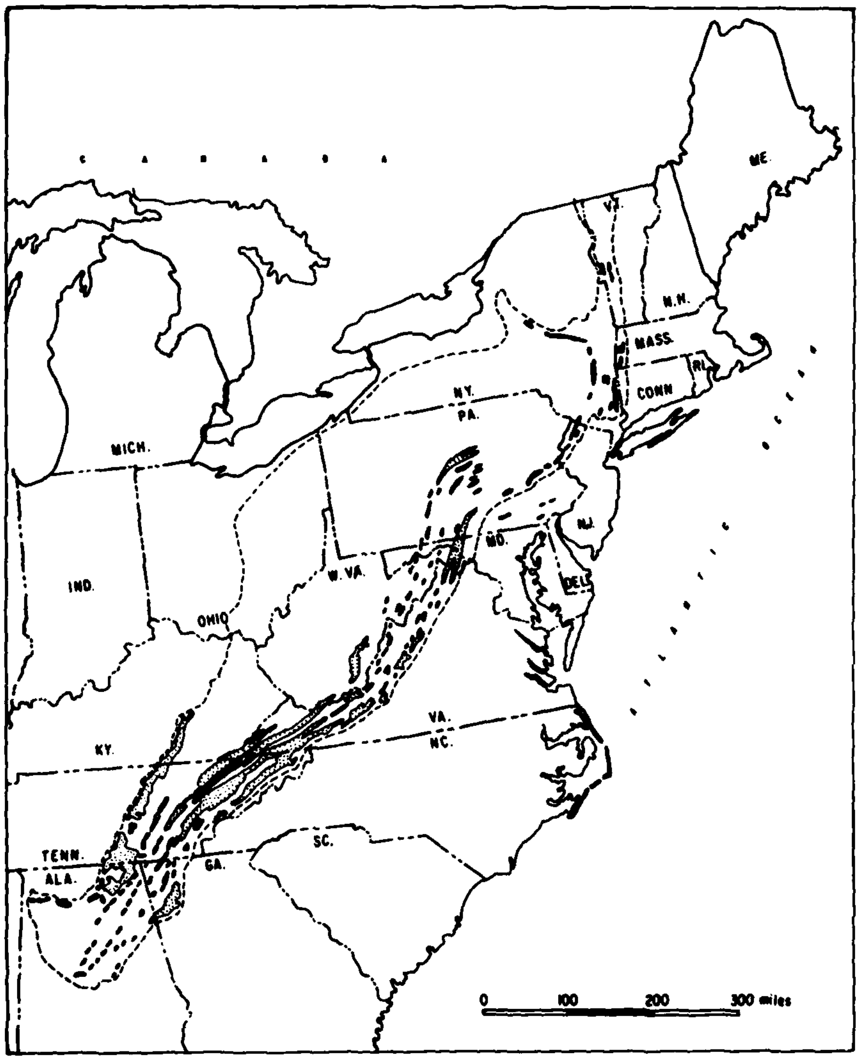


Figure 2.17. Appalachian karstlands (By W. E. Davies and H. E. Legrand, U. S. Geological Survey.)

across stratigraphic boundaries, are the best examples in the United States of karst in folded areas. The elevation of caverns is strongly controlled by the elevation of streams in adjacent entrenched valleys. Thus, stream terraces along these valleys are indicators of caverns in the valley walls which were active prior to entrenchment. The karst features in the more tightly folded portion of the Newer Appalachians lying to the west of the Great Valley are less extensive due in part to structure and the increased occurrence of nonsoluble clastic rocks. Often the caverns in the Newer Appalachians are straighter and less sinuous than those in the Appalachian Plateau Province to the west. The caverns in the Great Valley exhibiting rather simple patterns have been designated as Appalachian type to distinguish them from the more complex caves in the Appalachian Plateau Province (Figure 2.18).

The Appalachian Plateau

The province lies to the west of the folded Newer Appalachians and extends from southern New York State to Alabama (see Figures 2.16 and 2.17). The rocks in this region are predominantly Upper Paleozoic clastics. Karst-forming limestones of Mississippian Age occur in the central and southern portions, whereas Silurian and Devonian Age limestones occur in the north. The dips of these rocks are usually low. The location and extent of limestone outcrop is variable. Extensive karst features are present where the limestone forms the surface of a plateau; under such conditions uvalas may be common and the surface of the plateau may be quite irregular. In stream valleys along the sides of the plateau area, solution features occur in limestone forming the valley walls and valley floor. These features usually occur where tributary streams draining the plateau enter the master valleys. Solution in these tributary stream valleys has produced indentations along the master valley which are called coves. The coves consist of sinkholes, uvalas, and ponors. Numerous caverns exist in this province. Generally, the cave pattern is highly complex and multilevel and collapse structures are common. These complex patterns are referred to as Allegheny type to distinguish them from the simpler Appalachian type occurring in the Newer Appalachians.

Interior Low Plateaus

Probably the most extensive and diverse occurrence of true karst features within the United States is found in parts of Indiana, Kentucky, and Tennessee. Surficial and underground solution features have developed here upon and within relatively flat-lying Mississippian age limestones. From the standpoint of karst development, this province may be subdivided into two principal parts; namely, a region including southern

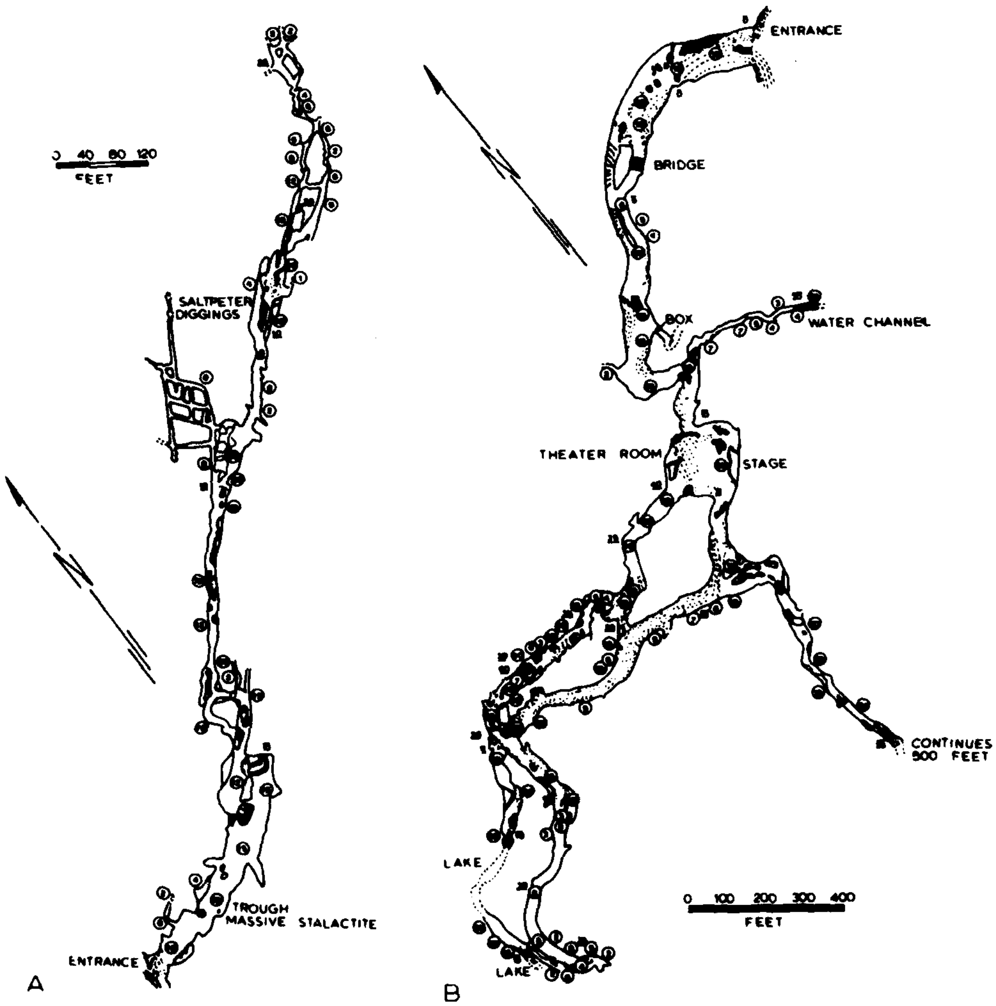


Figure 2.18. Plan of typical caves. (Numbers indicate ceiling height in feet.) A. Appalachian type, Trout Cave, West Virginia. B. Allegheny type, Laurel Creek Cave, West Virginia. (By W. E. Davies, U. S. Geological Survey)

Indiana and central Kentucky, and a region in central Tennessee. The Indiana-Kentucky region consists of karst lowlands, the Mitchell and Pennyroyal Plains and karst uplands, the Crawford Upland, and the Mammoth Cave Plateau. Generally, karst features are pronounced on both upland and lowland areas in Kentucky, whereas only the lowland exhibits well-developed karst in Indiana. Figure 2.19 shows the location of the karst areas in this region and Figure 2.20 shows the relation between the Crawford Upland and Mitchell Plain in Indiana. A similar relation between upland and lowland exists in Kentucky and this

Figure 2.19. Karst areas of central Kentucky and Indiana (by W. E. Davies and H. E. Legrand, U. S. Geological Survey)

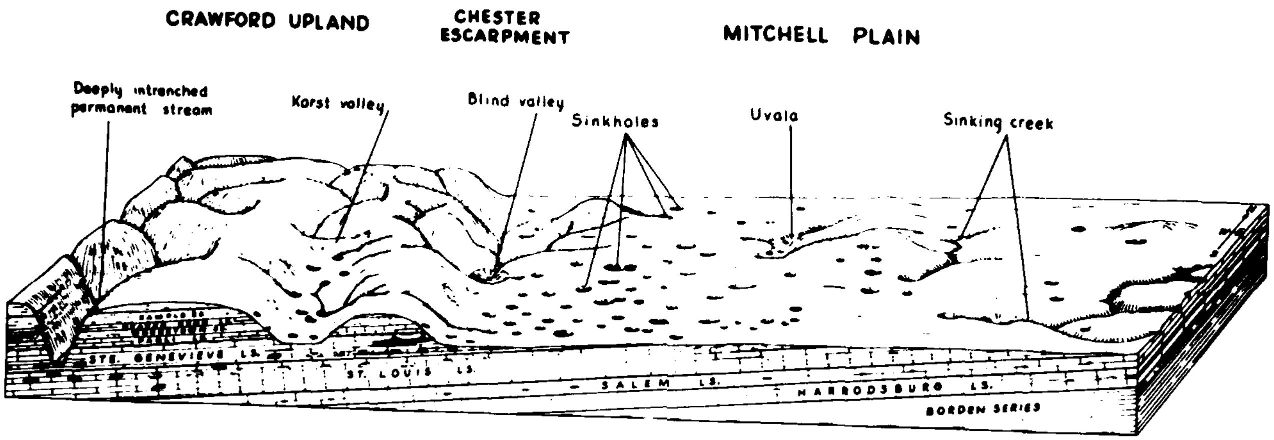


Figure 2.20. Idealized diagram of a portion of the karst area in southern Indiana (Thornbury, 1969.) Copyright, John Wiley & Sons, Inc. Reprinted by permission.

relation is shown on the topographic map reproduced in Figure 2.1. The karst in central Tennessee and Kentucky is developed upon Lower Paleozoic limestones occurring on the Nashville Plain and Lexington Plains. This karst area grades into the Highland Rim area of western Kentucky and Tennessee where karst is developed upon Mississippian Age limestone.

Ozark and Ouachita Plateaus

The development of extensive karst is generally restricted to the more northerly Ozark portion of this province in southern Missouri and northern Arkansas. Here, on the flank of the Ozark Dome, the occurrence of thick sequences of cherty limestones and dolomites of Paleozoic Age have produced widespread sinkholes and caverns. Usually, cave patterns are simple and exhibit one or two passages aligned along discontinuities; multilevel cave systems are not common. However, caves may occur at depths of 100 metres. The caves and cave-forming processes in Missouri have been described by Bretz (1956). This work should be consulted for details.

Atlantic and Gulf Coastal Plains

In the southeastern U. S., solution features are prevalent in Florida, Georgia, and the Carolinas (particularly South Carolina). The karst in this area is developed in limestones ranging in age from Eocene to Miocene. These rocks are the youngest materials in the U. S. in which extensive solution has occurred. The outcrop or near surface occurrences of these limestones is shown in Figure 2.21. Usually these materials do not exhibit extensive outcrop areas except along some stream valleys. Generally, the rocks are covered by either residual soils or, more commonly, by younger Tertiary or Pleistocene sands and clays. The residual clays in Georgia are terra rossa soils, whereas those in Florida are yellow and gray in color. Figure 2.22 illustrates the relation between the sands and clays and the underlying limestone. The limestone sequence, particularly in Florida, is characterized by sand and clay interbeds which indicate periods of emergence. Solution processes were initiated during these periods of Tertiary emergence; however, the most important periods of karst development occurred during and because

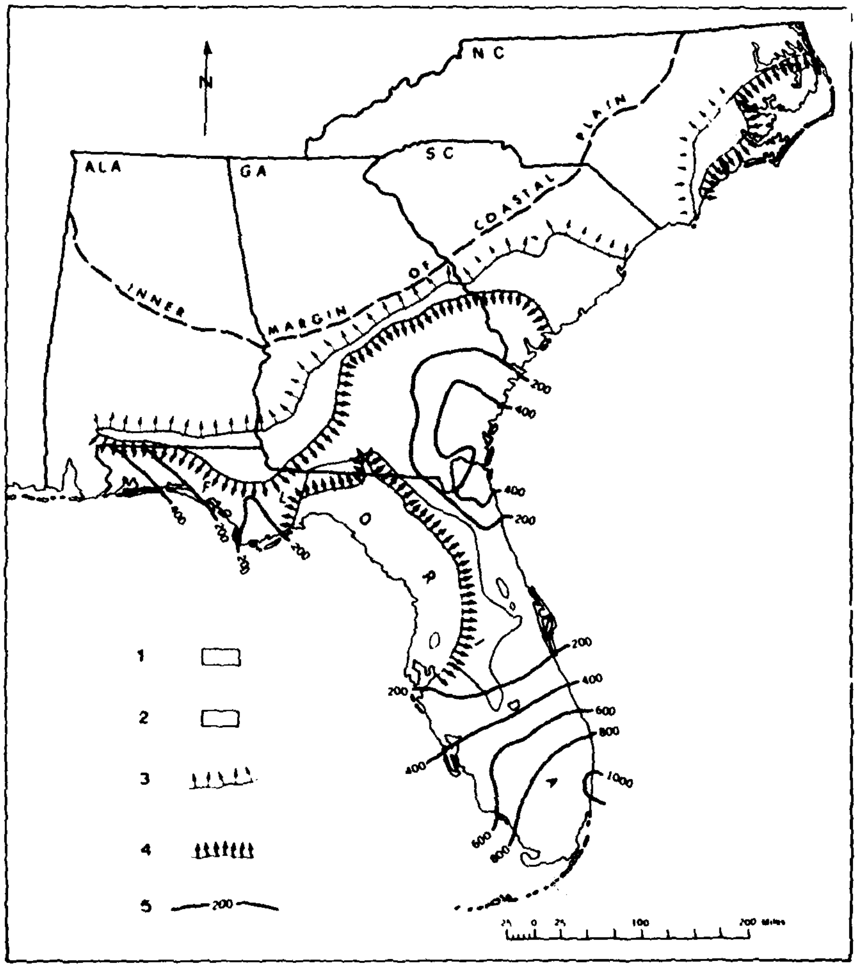


Figure 2.21. Outcrop areas of Tertiary limestone. 1: Tertiary limestone at or near surface; 2: Principal area of sinks which breach the Hawthorn formation; 3: Line north and west of which some thin patches of Tertiary limestone occur; 4: Line beyond which limestone thickens and is more deeply buried; 5: Contours on top of Tertiary limestone in feet below sea level (By V. T. Stringfield and H. E. Legrand, U. S. Geological Survey)

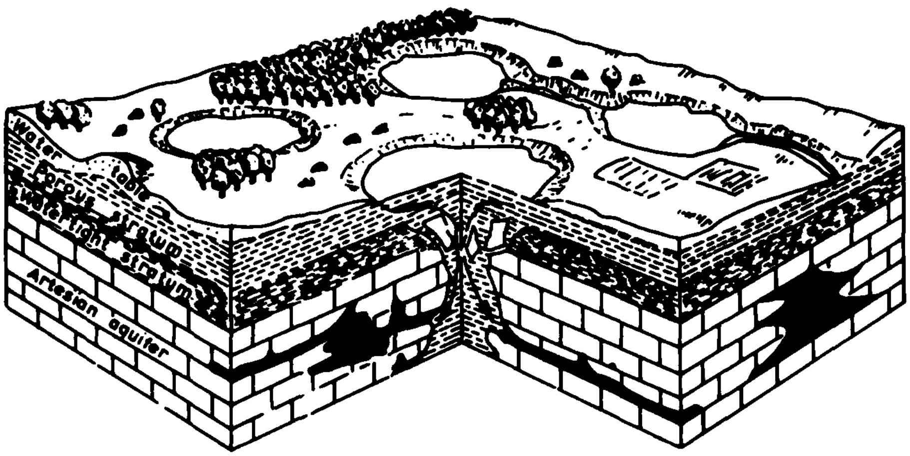


Figure 2.22. Sketch showing relation between karstic limestone and overlying soils in central Florida. Arrows indicate recharge of groundwater through sinkholes. (After Cooper and Kenner, 1953.)

of sea level changes in the Pleistocene. Many of the sinkholes, which may be partially filled with sand or clay, are perennial lakes due to the high water table and even, year-around precipitation. Subsidence and collapse of sinkholes occur locally due to excessive pumping of groundwater.

Great Plains

Karst features in this province occur on the Edwards Plateau area of south-central Texas, in the Pecos Valley of southeastern New Mexico, and in portions of western Oklahoma and central Kansas. On the Edwards plateau, sinks, collapse sinks, and caves occur in flat-lying Cretaceous limestone. Cavern patterns here are complex and multilevel. Along the Pecos Valley, particularly the western side in New Mexico, karst occurs in a stratigraphically complex sequence of Permian limestone, dolomite, and anhydrite. Except for limited occurrences to the east of the Pecos River, surface solution features are not common. Generally throughout much of the area solution has occurred horizontally along bedding planes in the evaporite facies. Extensive cavern formation, however, has occurred in limestone facies at great depths (300 metres) in the Carlsbad area. The origin of these deep caverns was controlled by several factors, namely, deep artesian groundwater flow occurrence from under the Guadalupe Mountains toward the Pecos Valley and Carlsbad areas to the east; stratigraphic control of the groundwater flow by the limestone reef facies; and greater susceptibility of this facies to solution than the surrounding facies by virtue of its composition. Karst features also occur in the Permian outcrop areas of Texas and Oklahoma. Here the solution generally occurs in Permian gypsum beds and is expressed by occasional collapse sinks and caves, of which Alabaster Caverns in northwest Oklahoma is the largest.

Other karst and pseudokarst areas

In the eastern United States, surficial and underground solution features also occur in New York State, Ohio, Michigan, and along the Upper Mississippi Valley in Illinois, Iowa, Wisconsin, and Minnesota. In the western United States, karst is a localized phenomenon occurring in most of the western states; however, it is not as extensive as in the east. A possible exception is the karst areas on the southeast and southwest sides of the Black Hills uplift area in South Dakota and Wyoming. The western karst, where present, often occurs where limestone units are exposed along the flanks of uplifted mountain areas such as the Black Hills, where several rather large caves occur. The lack of appreciable extensive karst may be attributable in part to drier climate and limited outcrop due to folding, and to cover by younger, nonsoluble units. The largest exposed area of flat-lying carbonate rocks is the southwestern part of the Colorado Plateau in Arizona; however, only minor karst has developed. Pseudokarst features, primarily developed in and upon lavas, are relatively abundant in the western U. S. These occur primarily on the Snake River Plain and other areas in the Columbia Plateau Province.

Other Underground Openings

The surficial and subsurface effects of mines and other man-made excavations or activities, particularly those located relatively near the earth's surface, may produce hazards that bear some similarity to those caused by karst or pseudokarst processes. These hazards include subsidence and collapse. Such failures may occur either by withdrawal of fluids such as groundwater or petroleum or by the gradual or sudden loss of strength in rocks and soils overlying mined-out areas. Subsidence caused by fluid withdrawal will not be addressed in this report.

Underground openings originating from mining activities include two distinct types. The first type are openings that have been excavated underground by following a particular ore body or stratum. Coal mines are common and often well documented examples of this type of mining; however, collapse may also be associated with lead-zinc mining and probably others. The second type, of less common occurrence, is solution mining of rock salt and some other soluble ores, in which water is injected into a borehole and the solution is pumped out at another borehole. The distinction between these two types is important because in the first case the excavation is more easily controlled and the extent of mined-out areas may be accurately known. On the other hand, the extent of the area mined out by solution mining may be imperfectly known.

The exploration program for areas believed to be underlain by mined openings should include some study of the nature and occurrence of the ore body and the techniques that were likely used (or are being used) to extract the ore. Since the nature and occurrence of the ore is a function of the regional geology, including historical geology, lithology, and stratigraphic and structural framework, this information would be a part of normal site evaluation. Information on mining techniques and the extent of mined out areas could be obtained from company records or from data collected by State and Federal agencies, if available.

However, in some areas, particularly those in which mining has been conducted for many years, records of mining activities may be incomplete or may not exist. Under these circumstances, exploration would have to be conducted almost exclusively on the basis of geological information, as would be the case in karst areas.

Although regions underlain by any type of mined-out areas are important, those regions underlain by coal mines and possibly salt mines are most important on the basis of number and extent as well as hazard potential.

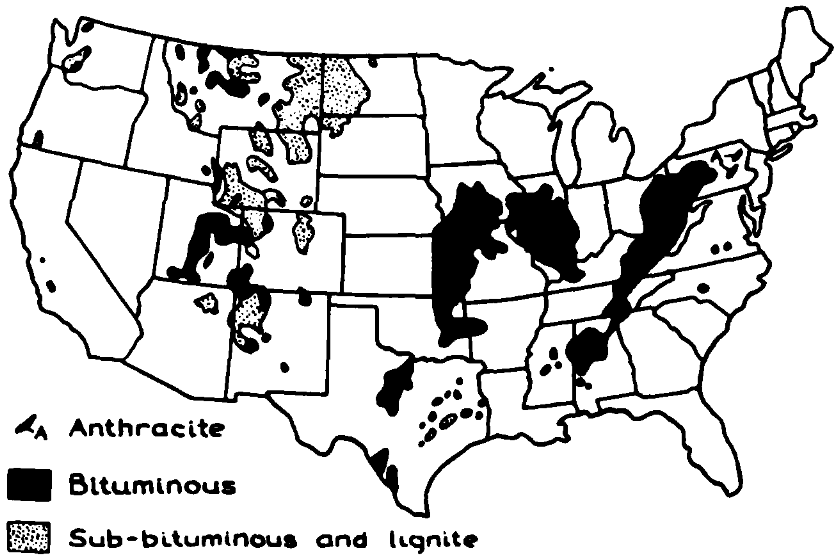


Figure 2.23. The coal fields of the United States. (From Principles of Geology, Fourth Edition, by James Gilluly, Aaron C. Waters, and A. O. Woodford. W. H. Freeman and Company. Copyright © 1975.)

Figures 2.23 and 2.24, respectively, illustrate the major coal and salt basins in the United States. For greater detail, see the U. S. National Atlas (U.S. Geological Survey, 1970b). For information on a local scale, a starting point would be maps and reports available at the various state geological surveys and the U. S. Geological Survey. Not all of the areas shown on these maps would necessarily be hazardous. However, the knowledge that potentially hazardous subsurface conditions may exist in portions of the basins would require some additional or more elaborate studies to be undertaken.

POTENTIAL INDICATORS OF SUBSURFACE OPENINGS

Table 2-1 provides a checklist of conditions or features that should be considered in determining whether a problem of possible ground collapse due to natural or man-made underground openings exists at a site, and in evaluating its extent or degree of severity. Identified as "direct indicators" are conditions or features (e.g., sinks, pepinos) that always or most often occur in association with processes that produce underground openings, so that their presence is a strong indicator of the likelihood of underground openings also occurring. Examples of "conditional indicators" are natural bridges, which occur as a result of karst processes, as shown in Figure 2.6, but not exclusively, since they are also produced by aeolian erosion of sandstone; and the presence of limestone, which will lead to the development of solution features only in combination with other contributory influences, such as favorable conditions of groundwater hydrology, stratigraphy, etc.

The degree of significance of the listed indicators varies a great deal more than the simple two-fold classification in the table can reflect, and the table also fails to show the great importance of the concurrence of multiple indicators. However, the occurrence of any of the direct or conditional indicators at a nuclear facilities site would be occasion for a conscious, explicit examination of the possibility that a problem of subsurface openings exists and a decision on what

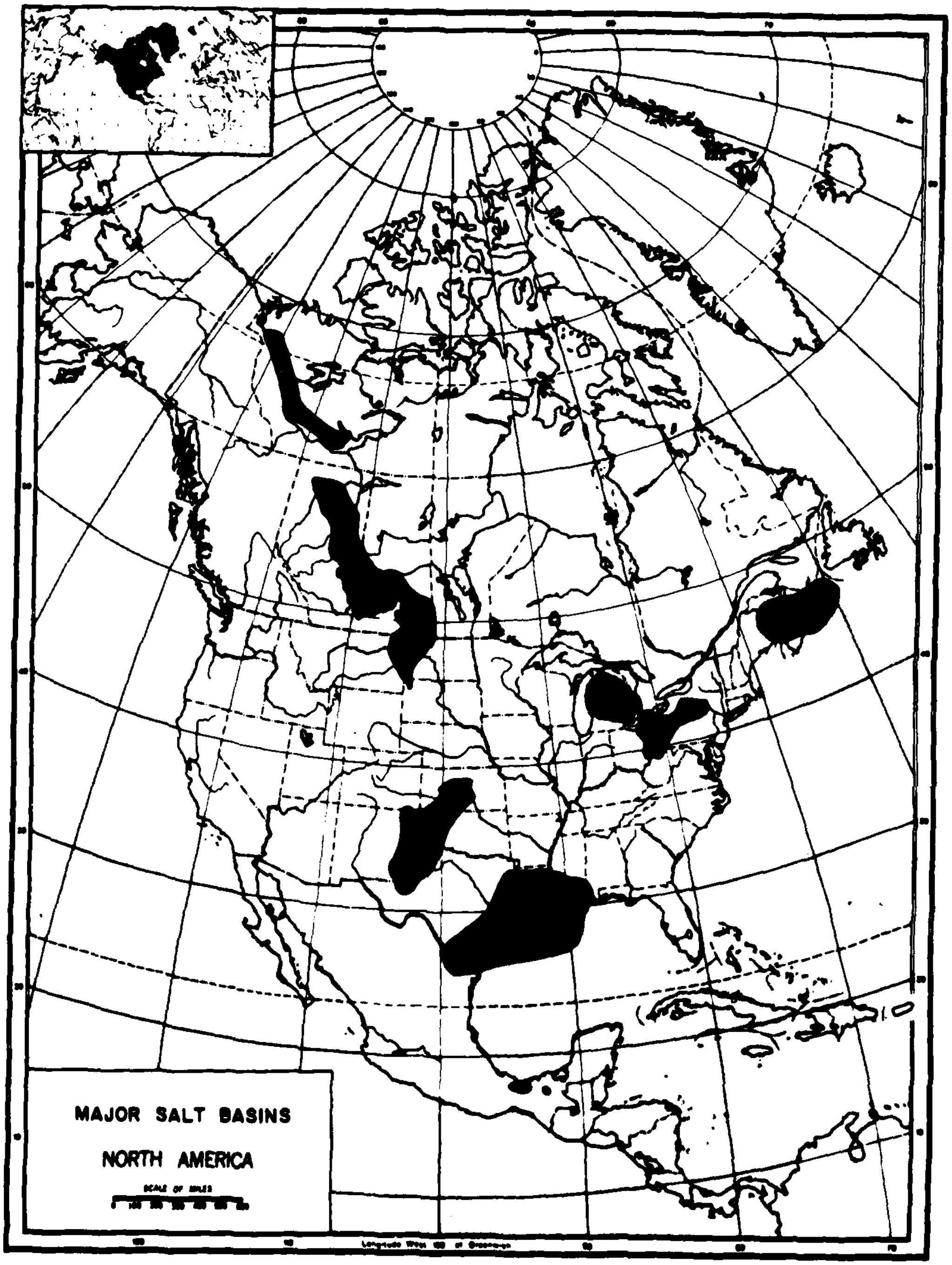


Figure 2.24. Major salt basins of North America (Landes, 1963)

additional investigations would be required.

"Modifying factors" shown in the table are those that affect, or reflect, the extent or degree of severity of the problem. Thus, they are factors that require study and explication in order to evaluate the extent of the problem, the hazard it offers, and the design of possible engineering remedies.

Table 2-1

Checklist of Potential Indicators of Subsurface Openings

	Direct Indicators	Conditional Indicators	Modifying Factors
Morphology	Sinks (sinkholes) Sink ponds Uvalas Hums or pepinos Caves, caverns	Natural bridges Surface depressions	Regional cave patterns Depth of caves
Hydrology	Sinking streams	Springs	Elevation of groundwater table Hydraulic gradients Confined aquifers Historical changes in groundwater levels Discharge and pumping rates Infiltration-runoff relations
Lithology		Limestones Dolomites Gypsum, anhydrite Halite (rock salt) Terra rossa soils Lavas Weakly cemented clastic rocks Coal or ores	Diagenesis; degree of dolomitization in limestones Permeability and porosity Mineralogy Cave filling materials Overburden soil type
Stratigraphy		Unconformity on soluble rocks	Thickness of soluble rock, lava, coal, or ore Presence and continuity of impermeable interbeds Facies relationships Age

Table 2-1 (Concluded)

		Direct Indicators	Conditional Indicators	Modifying Factors
	Structure			Density and orientation of discontinuities (joints, fractures, faults, bedding planes) Faulting Folding
Geomorphic	History	Historical ground subsidence		Base level changes Effects of stream enhancement
	Culture	Presence of mines or mining activities (shafts, adits, waste piles) History or records of mining activity or other subsurface excavations Underground fires		Age of activity Degree of extraction Pumping rates Groundwater usage

CHAPTER III: SITE INVESTIGATIONS - CONVENTIONAL METHODS

PLANNING

The planning and design of any major structure should include a program of site explorations with the general purposes of defining the site geology, which includes the stratigraphy, engineering properties of soils and rocks, structural geology, and faults and fractures; and defining any potential source of geological hazard such as cavernous bedrock. In evaluating problems raised by the possible occurrence of cavities, extensive use is made of information that is routinely obtained or is obtained for other purposes. Additional needed information is obtained from investigations directed specifically to the problem of detection and mapping of cavities. Discussions of methods of exploration in this report emphasize their use in detection, location, and delineation of subsurface openings.

The activities of a site investigation are frequently described as occurring in three phases. While these are variously described, they might be called for the present purposes (a) the preliminary phase, (b) the site-specific investigations, and (c) detailed exploration. These investigations progress, not necessarily in a strict time sequence, from preliminary assessment studies using the open literature, geological reports, available remote sensing imagery, and other paper sources, through field investigations of the general site conditions, to detailed delineation of site geology, hydrology, soils, and engineering properties of materials, including numerical values of engineering parameters. In the preliminary phase, the general geologic setting is established and the general nature of potential geotechnical problems is identified. Insofar as problems related to underground openings are concerned, this phase could be characterized as the one of prediction, and the considerations discussed in Chapter II play a major part. If there is a potential for possible solution or subsidence problems, it should be known at this stage, so that the on-site investigations can be planned or modified to develop the information needed to deal with the problem.

The design of the exploration program, the choice of the methods, and the relative emphasis given to various parts of the program will depend on the nature of the site and the project. Some factors involved in the planning of investigations for cavities are:

1. Geology of the site. Examples of characteristics that should be considered early in planning the site investigation include the thickness and nature of overburden soils, surface morphology (e.g., depressions), surface hydrology (e.g., surface drainage, springs, sinkholes), joint patterns, stratigraphy, and structural geology. Features such as lineations or linears seen in remote sensing imagery, as well as other anomalies that might be associated with solution activity, should be considered in laying out boring locations or locations and alignments of other exploratory surveys. The nature of cavities should be considered, especially whether they occur as discrete openings, such as tunnels or mine openings, or as networks of interconnected channels or solution-widened joints. In some instances where the latter case occurs, it may be impractical, or impossible, to locate or map individual cavities, so that the only practical approach is to map zones according to the degrees of continuity or competence of the rock. Such a circumstance would also have to be considered in the design or siting of structures.

2. Nature of the structure. Important considerations include size, foundation loading, function (e.g., load bearing vs. water retaining), and design -- especially the ability of the structure to bridge gaps in the foundation. For instance, if a structure can span gaps of a particular width in the foundation, that would establish a maximum size for isolated cavities that could be tolerated under that structure. This would in turn dictate requirements for resolution, spacing, and depth of geophysical and subsurface investigations. On the other hand, if the function of the structure is water retention, integrated networks of small cavities under the structure would usually be of more significance than isolated discrete cavities. For such a structure, an exploratory approach that emphasizes zonation may be most appropriate. Again, the engineering design may affect the need for detail and resolution

in mapping of cavities. The use of a positive cutoff wall through the zone of solution potential may reduce the need for detailed investigation of cavities, or confine it to the neighborhood of the cutoff. The general principle governing these considerations is that the possible modes of failure should be identified and analyzed in relation to the kinds of ground conditions that could contribute to such failure, and the exploration program should be designed to assure the detection of any subsurface feature of critical dimensions or qualities.

3. Coordination of investigations. The exploration program for a site should be viewed as an integrated whole, even though the exploration plan necessarily evolves and changes as its execution progresses. The various parts and phases of the program should be complementary and should provide just enough redundancy to assure that important foundation conditions are defined with confidence. This confidence should be a consensus in the minds of a group of responsible, knowledgeable professionals. That a considerable degree of redundancy is essential is clear from consideration of the inherent variability of soil and rock (often concealed by a superficial appearance of uniformity), the limits of reliability of any single exploratory tool, and the many unpleasant surprises that engineers and builders have faced in karst terrains over the years as results of inadequate exploration. Excessive redundancy means excessive costs. To a great degree this can be avoided by planning to make most effective use of all sources of information. For example, a construction excavation into the rock is one of the best and most reliable sources of information on rock conditions. Recognition of this in the planning stages can prevent wasteful efforts to define the subsurface conditions prior to excavation to a degree of detail that is not needed in the early stages of construction.

The balance of this report deals with technique and analysis. While it is not practical to make the point anew under every topical heading, it should be remembered that mere technique and analysis are worthless, even dangerous, if exercised without common sense and judgement. Numerical data obtained from tests, and transformations of those data produced by analysis, should be used as aids in the exercise of judgement. It is the intent of the authors to advocate this approach to the use of the methodologies described in this report.

HYDROLOGICAL INVESTIGATIONS

Since the groundwater regime is of prime importance in solution processes, definition of the groundwater conditions is essential to an understanding of past and present solution activity that may affect the site. Important features of the groundwater regime include the locations and gradients of groundwater tables or phreatic surfaces, water-bearing zones, flow channels, relations to surface flows, aquicludes, and groundwater chemistry. The groundwater regime is apt to be complex in a karstic environment, because of the major part played by large-scale solution features. Nevertheless, water tables are usually fairly well defined. According to Stringfield and Rapp(1977), "As a rule, the boundary between the zone of saturation and the zone of aeration is about as definite in carbonate rocks as in other rocks. The joints and solution passages and other openings generally form a network of connected openings that are filled with water up to the water table." In exceptions to the rule, however, groundwater flow may sometimes occur in conduits lying above the general water table. Possibly the most important difference between groundwater flow in karst terrains and in porous media is that conduit flow generally dominates in the karst terrain, both above and below the water table, so that flow velocities are often orders of magnitude greater in karst. Another consequence is that filtration, which acts in porous media to remove many contaminants from the water, is virtually absent in the karst environment.

Where foundation safety is the issue, the primary concerns are with location of groundwater tables and identification of any zones of concentrated groundwater flow that may indicate large openings. Also, observations of hydraulic gradients and their variations, as well as rates and directions of groundwater flow, may indicate the presence or distribution of subsurface openings, and their connectivity.

Piezometers

Piezometers indicate through pore pressure observations the locations of groundwater tables. Observations from an array of piezometers provide gradients or the distribution of gradients, which can be indicative of zones of groundwater flow. For example, at Wolf Creek Dam in south-central Kentucky, maps of piezometric contours at top of rock indicated zones in which underseepage was concentrated in solution-enlarged joints (Fetzer, 1979). Multiple piezometers installed with tips or screens isolated at the proper levels may be used to obtain the same kinds of information for multiple groundwater tables or multiple flow zones, where these occur. In important projects, piezometers permanently installed and monitored during the operational life of the structure can provide warning of the development of potentially dangerous conditions. Such installations are particularly appropriate for dams, spray ponds, canals, or other structures whose integrity or function would be affected by groundwater flow in solution features. Some care is required in the interpretation of piezometer readings where groundwater behavior is dominated by joint systems. Readings may depend on the extent to which the open section of the piezometer intersects joints in the saturated zone, and may thus be erratic or misleading. A survey of the characteristics of various types of piezometers, their installation, and use is provided in Engineering Manual 1110-2-1908 (U. S. Army, 1971).

Flow Tracing

Under certain conditions, temperature measurements in surface waters or groundwaters may be used to trace groundwater flow. At Wolf Creek Dam, the temperature of the deep reservoir water, generally less than 12C, is lower than that of the regional groundwater, 15C. The presence of groundwater at a temperature of 9.2C in borings in a zone on the downstream side of the dam was used to infer the presence of a zone of flow from the reservoir (Fetzer, 1979).

Most commonly, tracing of groundwater flow involves the introduction of some substance into the water in an area of suspected inflow or into well points or borings in an upstream area, and the detection of the substance in the water in boreholes, well points, or surface water at downstream points. Zotl (1977) describes experiments in the tracing of cave water flow in Kentucky using fluorescein dye and stained lycopodium spores that were introduced into sinkholes. Fluorescein is favored as a tracing material because it is visually detectable in very small concentrations and is nontoxic. Quinlan and Rowe (1978) described the use of new dyes that are adsorbed on cotton fabrics to facilitate detection. Radioactive tracer materials, particularly tritium, have been frequently used in groundwater studies (Aulenback et al., 1978; Burdon et al., 1963; Halevy and Nir, 1962; Kaufman, 1960, 1961; Kaufman and Orlob, 1956a,b; Kaufman and Todd, 1962; Knutsson and Forsberg, 1967; von Buttlar, 1959). The objections to the introduction of radioactive materials into groundwater are obvious; a more sophisticated approach which avoids these problems is the use of neutron-activatable tracers such as chlorides, iodides, and bromides, in which post-sampling neutron activation is used to detect the materials (Hoaser et al., 1978; Osmin, 1977). Another approach is to use the noble gases, helium, argon, krypton, and xenon. These gases are inert and nontoxic and do not react with or adsorb out on the soil or rock material in their path. However, the need for special analytical equipment has retarded their use (Carter et al., 1959; Herzberg and Mazor, 1979). Fluorocarbons, which are nontoxic, detectable in very small concentrations, and do not naturally occur in groundwaters, have also found favor as tracer materials (Randall and Schultz, 1976; Randall et al., 1977; Thompson, 1976). General reviews of tracer technology are given by Kaufman and Orbob (1956a,b) and Halevy and Nir (1962).

Milanović (1979) describes the use of the "geobomb" in the karst of Yugoslavia. This is an explosive device in a spherical case of about 10 cm diameter, weighted to produce neutral buoyancy, and detonated by an internal timing mechanism. It is introduced into the flow channel at a swallow hole or sink, and the location of the detonation is determined by trilateration from a surface geophone array.

Another geophysical method with particular applicability to tracing of groundwater flow is the measurement of electrical spontaneous potentials (SP) generated by electrokinetic interaction between moving groundwater and the containing rock. Cooper, et al (1981), describe SP measurements at the ground surface on the right abutment of Gathright Dam, Virginia. The surveys included a profile across an inferred subsurface flow channel from a swallow hole at elevation 1850 ft to a number of active seeps or springs some 400 ft lower, in the river bed below the dam, and some 2100 ft distant horizontally. Negative SP values as great as 600 millivolts were observed above the inferred zone of seepage. Other experience with SP measurements is reported by Bogoslovsky and Ogilvy (1970), Ogilvy, et al (1969), and Corwin and Hoover (1979). The method has not been widely used, and must still be considered experimental.

Water Pressure Tests

Water pressure tests, sometimes called packer tests, are used for determination of the in situ permeability of the rock mass. The test consists of the injection of water into a borehole (or a section of a borehole) at a constant pressure and flow rate. The section to be tested is isolated from the rest of the borehole by a single packer, if the bottom of the test section is at the bottom of the borehole, or two packers if the interval is above the bottom. Pressures are normally limited to values that would not be expected to increase the fracture width; a common criterion is to use a pressure no greater than the effective overburden pressure at the depth of injection. In Europe, the common practice is to use the Lugeon Test, in which the pressure is maintained at approximately 10 atmospheres and the "water take" is expressed in Lugeon units, or Lugeons. One Lugeon unit corresponds to a flow rate of 1 liter per minute per metre of borehole tested. In the United States, there are no standard test procedures or methods of interpretation, though recommended procedures have been published by the Corps of Engineers (US Army, 1961) and the US Bureau of Reclamation (1977). Permeability values or water take values derived from the test results can be used as local indices of the degree to which the rock contains interconnected void space or cavities. A map showing contours of these values can serve as one basis for zonation of the site in terms of the rock mass continuity or quality.

TEST GROUTING

Grouting is normally a remedial measure rather than an exploration method, but the importance of observations and records made during grouting should not be overlooked as a source of information on geological conditions. The Corps of Engineers commonly uses test grouting, i.e., experimental grouting operations on exploratory boreholes, to determine before construction the extent to which the subsurface materials are groutable (U. S. Army, 1960). Records of grout takes can indicate the distribution of underground openings and, to some extent, their geometry and volume. Mapping of contours of grout takes, like water takes in permeability tests, can be used to assist in zonation of the site in terms of rock quality. Examples of the interpretation of grout takes to infer the characteristics of fractures are given in the Grouting Manual of the Water Resources Commission, New South Wales (1977). Procedures and methods of grouting are also discussed in Grouting Methods and Equipment (U. S. Army, 1981).

REMOTE SENSING METHODS

Generically, the term remote sensing refers to the use of airborne or satellite-borne sensors to detect features on or in the earth. The oldest and still most important of these methods is the aerial camera. More recently developed methods include the use of such devices as airborne magnetometers, airborne radar, and various types of scanners which detect and record electromagnetic radiation to which photographic films are not sensitive. Remote sensing devices fall naturally into two categories according to the fundamental physical nature of the phenomena to which they respond. Force field sensors measure the intensity or the gradient of various components of the earth's magnetic, gravitational, or electrical fields. Radiation sensors, which include the conventional photographic camera, respond to electromagnetic radiation that is either emitted or reflected by the ground.

Force Field Sensors

The principles of operation of the various force field sensors are the same as those of the surface geophysical applications of the same measurements (which are discussed in the next chapter), but with the distinction that the measurements are made from a remote platform, i.e., an aircraft or satellite. The advantages gained by using remote methods of observation are in speed and economy of operations, and occasionally in accessibility to areas that are remote or in difficult terrain. The major disadvantage is a loss of resolution as compared to either surface or subsurface application of the methods. These remote sensing methods are very valuable in geological exploration at the regional scale, but in general the resolution is insufficient for practical application at the scale of a site investigation.

Radiation Sensors

Radiation sensors respond to electromagnetic radiation in various frequency ranges which is either emitted or reflected by the ground or other objects. The source of reflected radiation may be natural (e.g., the sun) or artificial (e.g., electric lights, flares, or radar transmitters). The most important emitted radiation represents energy absorbed from sunlight and re-radiated in the infrared range. Comprehensive reviews of remote sensing methods and equipment are given in Engineer Pamphlet 70-1-1 (U. S. Army, 1979b) and in the Manual of Remote Sensing (American Society of Photogrammetry, 1975). Engineer Pamphlet 70-1-1 also provides an exhaustive review of sources of remote sensing data. The Manual of Remote Sensing places a greater emphasis on the interpretation of remote sensing imagery. Other useful texts on remote sensing methods, applications, and interpretation are those of Lintz and Simonette (1976), Sabins (1978), and Lillesand and Kiefer (1979).

Remote sensing imagery, particularly aerial photography, is a highly useful, even indispensable, tool in the geological exploration of a nuclear plant site. It is important to understand, however, that the information obtained by radiation sensors reflects conditions at the ground surface or, at most, the upper few centimetres of the ground. The interpretation of subsurface conditions relies totally on inferences drawn from observable surface conditions. For example, a subsurface cavity or opening may have associated with it one or more surface anomalies, such as a surface depression, a soil moisture anomaly, or an anomaly in the type or development of vegetation. Any of these might under some conditions imply the possibility of subsurface cavities. However, there is no direct response to the presence of a cavity itself.

Aerial photography

As mentioned above, aerial photography is the oldest, most frequently used and most important form of remote sensing (American Society of Photogrammetry, 1960, 1966, 1968). For most areas in the United States, existing photography is easily available at low cost. Also, for most parts of the world, earth satellite photography, which provides imagery on a regional scale, is available. These photographs are useful primarily for regional interpretation of geologic structure, soil and rock types, drainage patterns, and major landforms. For project site evaluations, conventional aerial photographs at a scale of 1:25000 or greater are most useful. Geological interpretation of aerial photographs relies on geomorphology plus the use of grey tones or colors that may be associated with particular rock types, vegetation growth, or soil conditions, especially soil moisture. Special photographic emulsions, such as color, infrared, or false-color infrared, may be used to enhance particular aspects of the photographic image, such as the kind and condition of vegetation. Improved discrimination may often be achieved through complementary use of emulsions that are sensitive to different parts of the electromagnetic spectrum (multispectral photography). Recognition of potential solution activity is achieved by the identification of geomorphological features associated with karst terrains, as discussed in Chapter II. Detection of specific cavities on aerial photographs is sometimes possible because subsurface features such as caverns, mine openings, or solution-widened joints sometimes have a very subtle surface expression that may be apparent on the aerial photograph though not to the ground observer. This most often occurs through anomalies of moisture content caused by subtle topographic effects and visible in the photograph through a difference in color or grey tone. However, there are no guarantees that specific cavities, even near-surface ones, can be detected. For general discussions of geological interpretation of aerial photographs, see: American Society of Photogrammetry, 1960, 1968; Miller and Miller, 1961; Lueder, 1959; Ray, 1960; Lattman and Ray, 1965.

Scanning devices

Scanners have a totally different principle of operation from that of the photographic camera. Some types of electromagnetic radiation, such as thermal infrared, cannot practically be used to produce an image directly on photographic film; however, the radiation can be gathered and focused on a sensing element by a mirror of suitable size and shape. The mirror can be swept so as to measure the radiation being received from different parts of the terrain. The sweep of a cathode ray tube can be synchronized with the sweep of the mirror to produce a television-like image. Various parts of the electromagnetic spectrum may be used for imagery of this type. That of greatest utility in study of soil and rock conditions is the mid- and far-infrared (1.1 - 15.0 μm). The far-infrared band (5.5 - 15.0 μm) is also known as the thermal infrared. The energy detected by the sensor derives ultimately from sunlight absorbed by the ground, heating materials at or near the surface; the heat energy being then re-radiated in the form of infrared radiation whose intensity depends on the surface temperature. A small amount of the heat energy comes from the internal heat of the earth, but this is insignificant in comparison with that derived from insolation. Thermal infrared imagery is a sensitive indicator of ground temperature, and is capable of indicating differences of the order of 1C. Thermal infrared imagery has been used for surveys of the efficiency of housing insulation and for detection of water damage in roofs of other structures (Link, 1978). Thermal anomalies in the ground are usually associated with soil moisture conditions, since higher moisture contents in soils are associated with greater thermal inertia. A subsurface cavity could have an associated subtle surface depression, and thus a moisture anomaly, or, if it is empty and communicates with the outside air, could be at a temperature higher or lower than that of the surrounding rock. Such effects could be expected to produce indications of subsurface cavities on thermal imagery under favorable conditions, and thermal imagery has been used sometimes with success and sometimes without success in attempts to detect cavities (Link, 1970, 1978). Thermal infrared imagery is also a sensitive indicator of surface water temperatures, and has been used an an indicator of underwater springs, thermal pollution of streams by industrial facilities, and reservoir leakage (Fisher, 1974).

Airborne radar surveys, of which the most commonly known is side-looking airborne radar (SLAR), uses a transmitter of radio energy in the microwave range (1.0 mm - 1.0 m) and receives the energy reflected from the ground surface. The radar scans along a line perpendicular to the line of flight of the aircraft and produces an image of an area to the side of, rather than directly under, the aircraft. The response is to the geometry of the surface scanned; that is, the amount of reflected energy seen by the receiver depends on the orientation of the surface with respect to the illumination by the radar transmitter and on the roughness of the surface. The image is not affected by the color, temperature, or other material conditions of the soil, nor by subsurface conditions. The energy penetrates foliage only to a minor degree. Resolution typically is of the order of 15 m. SLAR imagery has often been found useful for mapping structural features, because the illumination angle can be chosen so that subtle details of topography are enhanced through highlights and shadows. This is particularly effective for showing linear features such as the expressions of faults or fractures. Since the energy measured is reflected at or very near the ground surface, interpretation of subsurface conditions can be done only by inference from the surface geometry (American Society of Photogrammetry, 1975; U. S. Army, 1979b; Sabins, 1978; Sabins et al., 1980).

DRILLING AND EXCAVATION

From a review of the capabilities and limitations of exploration methods discussed in this and the following chapter, the inescapable conclusion is that the only way to obtain direct, definitive knowledge of the presence or absence of rock at a specific point in the subsurface, and its condition if present, is to obtain access to that point for visual observations or mechanical tests. That is, it is necessary to drill a hole through the point or open an excavation to it. For this reason, the final verification of foundations of critical structures must, in the present state of the art, be made by these direct methods.

Accessible Excavations

Accessible excavations--openings large enough for personnel entry and direct visual observation--are relatively expensive, but frequently justified in the case of critical structures. Pits or shafts are openings that are excavated vertically from the ground surface for access and direct observation. Pits are used primarily in soil exploration or to observe the overburden-bedrock contact conditions. Trenches are limited to relatively shallow depths, and are frequently used for fault investigations. They are also useful for joint mapping and for observation of overburden-bedrock contact conditions. At Hartsville

Nuclear Plant, in Tennessee, a large-scale preconstruction excavation made by stripping away overburden near the spray pond area permitted direct observation of the joint patterns, their orientation, and the character of solution openings (Figure 3.1). Excavations made for construction purposes offer a great deal of opportunity to acquire information on the overburden-bedrock contact, joints and joint patterns, and possible solution features. Further observations of solution activity at the Hartsville site were obtained by rock excavations for the

Figure 3.1. Solution-widened joints at Hartsville Nuclear Plant.

cooling water conduits (Figure 5.19) and for the containment buildings. Visual mapping of joints in the exposed rock of the containment building excavations indicated only minor solution activity in those areas. The solution-susceptible zone was nevertheless investigated by means of closely spaced drill holes at the containment building sites, and the results were consistent with conditions inferred from the joint maps.

Drilling

In the absence of direct physical access to underground openings, conventional drilling is the best and the most reliable source of information. During exploratory drilling, evidence of the lack of rock integrity may be found in instances of loss of circulation, influx of water into the drill hole, the dropping of rods, abnormally low drilling resistance or high penetration rates, or poor core recovery. Because of the implications of such occurrences, it is important that complete and careful records be made of all drilling operations. Drilling rate records, either mechanically made or by drillers' observations, should be routinely obtained.

Drilling methods in use today represent essentially 1940's technology, and are comprehensively described and discussed by Hvorslev (1949). Use of various methods of drilling in nuclear power plant site explorations is discussed in Regulatory Guide 1.132 (U. S. Nuclear Regulatory Commission, 1977). In sampling operations in rock, rotary drilling is most commonly used, and is generally the most efficient and cost-effective method. In site investigations where underground openings are suspected, two other methods have special applicability. The calyx drill, which is listed in Regulatory Guide 1.132 and by Hvorslev (1949) as a method of sampling, is particularly useful for drilling large-diameter holes that can provide personnel access, although it may offer problems of difficulty in drilling where lost circulation is encountered. Air-operated percussion drills, such as the air-track (Figure 3.2) or wagon drill, which are commonly used for rock bolt installation and for shothole

Figure 3.2. Percussion drill at Hartsville Nuclear Plant.

drilling in quarries, provide an economical way of drilling small-diameter, closely spaced holes for detailed foundation verification. While no intact samples are obtained, careful observation and logging of the drilling rates provide a reliable indication of subsurface cavities, whether empty or containing filling materials. A well-trained and experienced inspector is critical to the success of this method. Since solution-widened joints are usually near-vertical in orientation, exploratory drilling for them should include inclined boreholes. Percussion drills can be readily operated in an inclined position. Percussion drills were used at Hartsville Nuclear Power Plant in detailed foundation verification for Category I structures.

Rock core samples, which can be obtained with conventional rotary core drills or in hard rock with diamond core drills, permit highly detailed geologic examination and description and laboratory tests of physical, chemical, and engineering properties; and afterward are valuable as archival records. Evidence of fractures or other openings in rock, or the presence of infilling materials, may sometimes be seen in rock core samples, although more often, highly fractured or cavernous rock results in poor or no core recovery in those intervals. The degree of core recovery, expressed as the percent ratio of length of core recovered to length of interval cored, can be used as an index for classification and mapping of the quality or continuity of a rock interval. An alternative method of classification which has gained wide acceptance is the Rock Quality Designation (RQD), obtained by counting, in summing the total length of core recovered, only those pieces of core that are 4 in. (10 cm) or more in length, and that are hard and sound. (Pieces broken by drilling or handling, so that the fracture surfaces are fresh, irregular breaks, are fitted together and counted as one piece.) The result is expressed as a percentage of the length of the interval cored. A classification based on RQD is given by Deere (1968), and shown in Table 3-1.

Table 3-1. Classification of Rock Quality (Deere, 1968)

Rock Quality Designation (RQD)	Description of Rock Quality
0 - 25	Very Poor
25 - 50	Poor
50 - 75	Fair
75 - 90	Good
90 - 100	Excellent

Some statistical studies of the relation between RQD and fracture spacing are described by Goodman and Smith (1980).

A method of sampling that better preserves intervals of soft or incompetent rock and fractured zones is described by Rocha (1973). This method, called oriented integral sampling, yields samples more suitable for visual examination than conventional core samples, particularly where lack of core recovery is due to fracturing, but the samples are less useful for mechanical properties tests. In this method, a small-diameter hole is drilled, a rod is grouted into the hole, and it is then overcored with a larger diameter core drill. The core sample is held together by the rod grouted into its center.

Special precautions are required where highly soluble minerals such as halite may be present, as they will simply dissolve in the drilling mud and remain unseen. Air drilling or the use of salt muds or oil-base muds may be called for in such cases.

BOREHOLE SURVEYS

In the operation of drilling the hole, information on rock conditions is obtained from samples in the form of cores or cuttings returned by the drilling fluid, rate or resistance data, and events such as loss of circulation or influx of water into the hole. The generic term borehole surveys is used for methods of examining the materials at and around the borehole face by means of devices that are lowered into the hole. These include geophysical observations of the rocks in the neighborhood of the borehole, such as measurements of electrical resistivity, gamma ray emission, response to neutron bombardment, seismic velocity, gravity gradient, and temperature; and measurements or observations of the condition or geometry of the borehole itself, such as caliper measurements of borehole diameter, borehole cameras, and deviation surveys. Methods of borehole logging and their interpretation are described in Engineer Manual 1110-1-1802 (U. S. Army, 1979a); Schlumberger (1972, 1974); Seismograph Service Corporation (1973); Pirson (1963); Tittman (1956); and Tittman and Wahl (1965). Table 3-2 lists several types or categories of borehole survey methods that are useful in

Table 3-2

Borehole Surveys

Method	Procedure and Measurements	Applicability	Limitations	References
Elastic Velocity Log	Logging tool contains transmitting transducer and two receiving transducers separated by fixed gage length. Signal is transmitted through rock adjacent to borehole and transit time over the gage length is recorded as difference in arrival times at the receivers.	Measurement of compression wave velocity. Used primarily in rocks to obtain estimate of porosity. Indicates fracture zones.	Results represent only the material immediately adjacent to the borehole. Can be obtained only in uncased, fluid-filled borehole. Use is limited to materials with P-wave velocity greater than that of borehole fluid.	Schlumberger, Ltd. (1972)
3-D Velocity Log	Logging tool contains transmitting transducer and receiving transducer separated by fixed gage length. Signal is transmitted through rock adjacent to borehole, and wave train at receiver is recorded.	Measurement of compression wave and shear wave velocities in rock. Detection of void spaces, open fractures, and zones of weakness.	Results represent only the material immediately adjacent to the borehole. Can be obtained only in uncased, fluid-filled borehole. Correction required for variation in hole size. Use is limited to materials with P-wave velocity greater than that of borehole fluid.	Geyer and Myung (1971)

Table 3-2 (Continued)

Method	Procedure and Measurements	Applicability	Limitations	References
Spontaneous Potential (SP) Log	Logging tool measures spontaneous potential between borehole fluid at depth and an electrode at the surface.	In conjunction with electrical resistivity surveys, is an indicator of porous zones. Provides measurement of pore water resistivity.	Use is limited to fluid-filled, uncased boreholes.	Pirson (1963), Schlumberger (1972, 1974), Seismograph Service Corporation (1973)
Electrical Resistivity Log	Apparent electrical resistivity of soil or rock in neighborhood of borehole is measured by in-hole logging tool containing one of a wide variety of electrode configurations. Depth of investigation is governed by electrode spacing.	Appropriate combinations of electrical logs can be used to estimate porosity and degree of water saturation in rocks, and probable lithology.	Can be obtained only in uncased boreholes. Hole must be fluid filled, or electrodes must be pressed against wall of hole. Apparent resistivity values are strongly affected by changes in hole diameter, strata thickness, resistivity contrast between adjacent strata, resistivity of drilling fluid, etc.	Pirson (1963), Schlumberger (1972, 1974), Seismograph Service Corporation (1973)

Table 3-2 (Continued)

Method	Procedure and Measurements	Applicability	Limitations	References
Neutron Log	Neutrons are emitted into rock or soil around borehole by a neutron source in the logging tool, and a detector isolated from the source responds to either slow neutrons or secondary gamma rays. Response of detector is recorded.	Correlation of strata between boreholes and location of strata boundaries. Provides an approximation to water content and can be run in cased or uncased, fluid-filled or empty boreholes.	Because of very strong borehole effects, results are generally not of sufficient accuracy for quantitative engineering uses.	Pirson (1963), Schlumberger (1972, 1974), Seismograph Service Corporation (1973), Tittman (1956)
Gamma Ray Log	Intensity of natural gamma radiation emitted by the formation is measured.	Responds to radioactive minerals and to radioisotopes occurring in clays. Used primarily as a qualitative indicator of clay versus nonclay rocks and for lithologic and stratigraphic correlation between boreholes.		Pirson (1963), Schlumberger (1972, 1974), Seismograph Service Corporation (1973)

Table 3-2 (Continued)

Method	Procedure and Measurements	Applicability	Limitations	References
Gamma-Gamma Log ("Density Log")	Gamma rays are emitted into rock around the borehole by a source in the logging tool, and a detector isolated *from* the source responds to back-scattered gamma rays. Response of detector is recorded.	Estimation of bulk density in rocks, qualitative indication of changes in density of soils. May be run in empty or fluid-filled holes.	Effects of borehole size and density of drilling fluid must be accounted for.	Schlumberger (1972, 1974), Seismograph Service Corporation (1973), Tittman and Wahl (1965)
Borehole Cameras	Film-type or television camera in a suitable protective container is used for observation of walls of borehole. 3-D Photo Log uses stereo camera.	Detection and mapping of joints, seams, cavities, or other visually observable features in rock. Can be used in empty, uncased holes or in holes filled with clear water.	Results are affected by any condition that affects visibility.	Lundgren et al. (1970), Prakla-Seismos (1978)

Table 3-2 (Continued)

Method	Procedure and Measurements	Applicability	Limitations	References
Caliper	Diameter of borehole measured with mechanical caliper.	Measurement of mud cake thickness, detection of washouts, cavities, clay seams, fractures.		Pirson (1963)
Televiewer	Borehole is scanned by rotating acoustic transducer-receiver.	Detection of fractures, cavities, washouts, orientation of fractures.		Zemanek, et al. (1968)
Temperature	Temperature of the fluid in the borehole is measured by thermistor.	Detection of gas entry, water movements; measurement of geothermal gradient.		Pirson (1963)
Echo-Log	Interior of cavity is scanned by ultrasonic transducer-receiver in fluid-filled holes, or laser range finder in air-filled holes. Tool head has rotating and tilting movements.	Mapping interior of fluid-filled or air-filled cavities through borehole access.		Prakla-Seismos (1978)

Table 3-2 (Concluded)

Method	Procedure and Measurements	Applicability	Limitations	References
Directional Survey	Amount and direction of borehole inclination is measured.	Determine true position in space of features detected or measured in borehole. Normally run in conjunction with other surveys.	Accuracy degrades with depth.	

general exploration in boreholes or for application to surveys of potential underground cavities.

Conventional geophysical logs provide a great deal of information on the general lithology and condition of the rock in the neighborhood of the borehole. The most common are the spontaneous potential, electrical resistivity, gamma ray, and gamma ray-neutron (see Table 3-2). The observations made are complementary, and they are most effectively used as a suite of logs. The information obtained reflects conditions throughout some volume of rock in the vicinity of the boreholes, and in general does not have directional qualities. Thus, geophysical logs are useful primarily for detection and delineation of zones of solution activity or increased porosity, rather than for detection of specific, discrete cavities. An exception is the use of electromagnetic radiation in the form of radar, which is discussed in Chapter IV.

Survey methods that are directed at surveying the shape of the borehole are of the greatest interest in the exploration of cavities. Such methods include caliper logs, borehole camera or television, the televiewer, and the Echo Log (see references cited in Tabel 3-2). The last named of these methods is specifically designed for the investigation of cavities. In all such methods, an obvious requirement is that the borehole intersect the cavity to be investigated.

PROBABILISTIC CONSIDERATIONS IN PLANNING AN EXPLORATION PROGRAM

To a limited extent, probability models are available to describe the presence of subsurface cavities at a site and to guide the allocation of exploration effort to detect these cavities. In general terms, the problem of search in geotechnical exploration is to locate an anomaly of a particular description in an efficient way, or to disprove its existence, based on an initial probabilistic description of its location and the uncertainty in interpreting field data. At this time, no comprehensive, systematic methodology has been developed to formally optimize the process of site exploration. Investigations for geological details rely primarily on judgment based on experience and knowledge of geology; thus, it is basically subjective, and probabilistic, mathematical models are only tools to ensure against mistakes in logic (Baecher, 1978).

Most of the mathematical models for detection are in the general category of geometric probability (Kendall and Moran, 1963), and search theory (Morse, 1974). Several workers in economic geology, (e.g., Drew, 1966; Singer and Wickman, 1969) have applied these techniques to geological exploration to analyze grid search and other systematic allocations of borings, geophysical traverses, and other search methods. As a result of this work, tables of probability of detection have been calculated for a variety of grid and target geometries.

The theory of optimal search was developed during World War II under the U. S. Office of Naval Research, by Koopman (1956a,b,c; 1957) for application to seaborne search (e.g., submarines, lost pilots) and is now referred to as Koopman optimal search theory. Much of this theory has been further advanced in its more recent applications to mineral exploration (de Guenin, 1961). For example, two-stage search has been analyzed by Allais (1957) for exploration of the Sahara and by Engle (1957) for exploration of clustered deposits. One objective of researchers has been to infer statistically the volume of undiscovered deposits in the ground. In general, these analyses do not deal with optimal allocation of search effort, but how to use present information to make estimates (De Geoffroy et al., 1970; Uhler and Bradley, 1970). Statistical decision theory, which weighs risks and exploration costs against monetary consequences, has been applied in oil exploration by Kaufman (1963). Only a few researchers have analyzed the application of search theory to detection of anomalies and post-investigation estimation of the probability that anomalies exist at a site or are as yet undetected. A series of theses at MIT has dealt with search in geotechnical exploration in general terms (Baecher, 1972) and as applied to sink holes and limestone cavities by Grant (1973) and Drake (1976). Rosenblueth, in some unpublished work, has applied probability theory to detection of abandoned mines in Mexico (Baecher, 1978).

A major shortcoming of the published applications of probability and search theory to exploration is that the location of each target, such as a solution cavity or channel, must be assumed to be independent of the location of any other target. This assumption does not describe the nature of solution channels and cavities, or mines, which tend to have locations that are somewhat periodic or occur as a network. Despite this limitation, some general guidance can be gleaned from the results of search theory. The following discussion of detection probabilities associated with various exploration grids is limited to sites for which there is no prior information as to the location of a target, so that exploration effort is uniformly distributed over the site.

Random Search

Before turning to grid-type allocation of search effort, a few comments should be made about random search. Common sense indicates that random search is inefficient, and this can be shown analytically. Since the question of allocating boreholes by means of a table of random numbers is often posed, a comparison is made here between the probability of locating a target by means of randomly located borings and an equal number of uniformly placed boreholes.

Let us assume that a site of area A_s has exactly one target of area A_t The probability of any randomly located boring intersecting the target is:

$$P\left[\text{find} \mid 1 \text{ boring}\right] = A_t/A_s \tag{3-1}$$

The probability that the target is located with n borings is:

$$\begin{aligned} P\left[\text{find} \mid n \text{ borings}\right] &= 1-P\left[\text{no find} \mid n \text{ borings}\right] \\ &= 1 - \left\{1 - \frac{A_t}{A_s}\right\}^n \end{aligned} \tag{3-2}$$

For $(A_t/A_s) \leq 0.1$, this is approximately:

$$P\left[\text{find} \mid n \text{ borings}\right] \approx 1 - e^{-n(A_t/A_s)} \quad (3\text{-}3)$$

Equations 3-2 and 3-3 will give a nearly linear relationship between the probability of finding the target and the value of n , until n becomes quite large; then the relationship becomes nonlinear, reflecting the increasing probability that more than one boring will interesect the target. Figure 3.3 shows the relationship between the probability

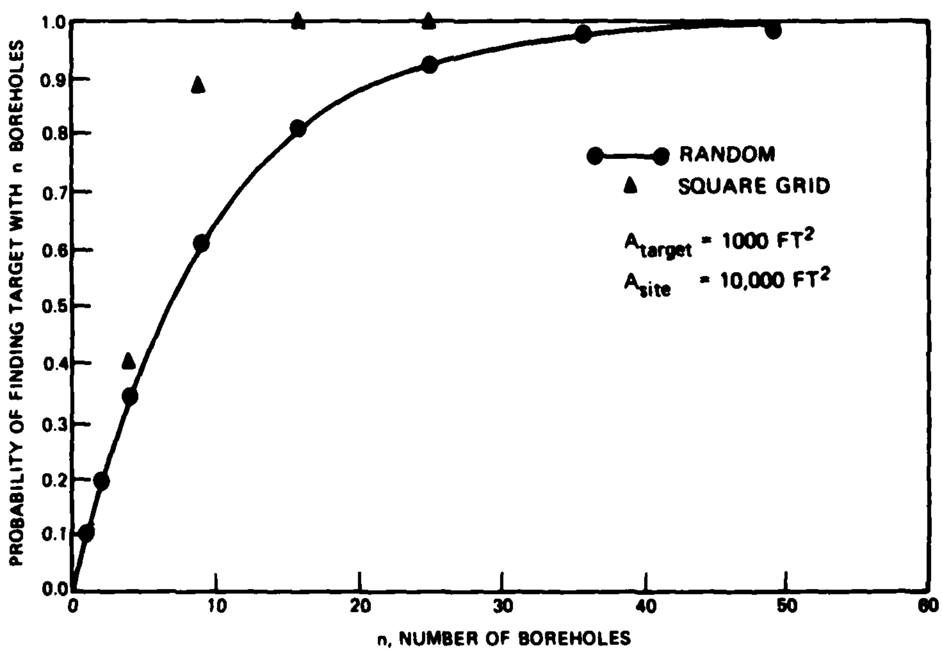
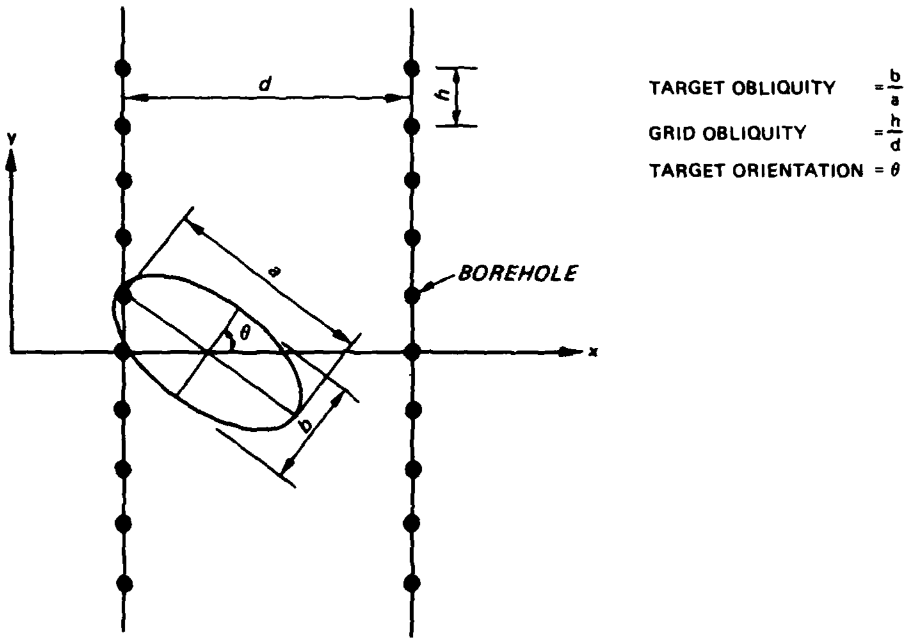


Figure 3.3. Probability of finding a target with rectangular grids and randomly located borings. $A_t/A_s = 0.1$

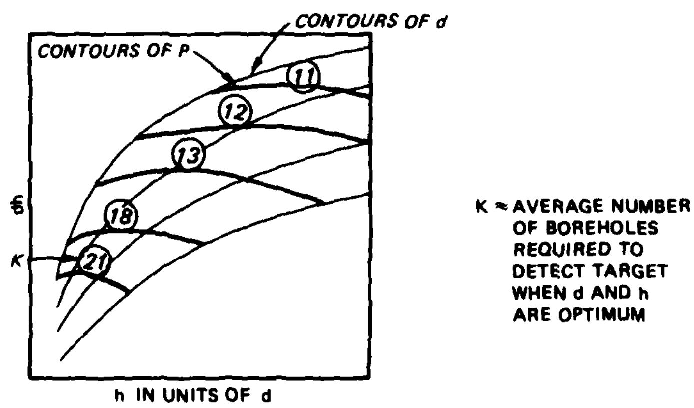
of a find and the number of randomly located borings for the ratio A_t/A_s equal to 0.1. On the same figure is plotted the probability of a find for an equal number of boreholes on a square grid at a site 100 ft square with a circular target of diameter 35.68 ft and an area 1000 ft^2 ($A_t/A_s = 0.1$). The greater efficiency of uniform grid allocation of borings is clearly evident from this figure. For n = 16 borings, the randomly located scheme has only an 81 percent probability of finding the target, whereas the uniformly spaced square grid is sure to find the target, $P\left[\text{find} \mid n = 16, \text{square grid}\right] = 1.0$.

Uniform Search with Point Grids

Although few publications address probabilistic approaches for planning geophysical surveys, the efficiency of alternative boring layouts has been investigated from a probabilistic viewpoint. Probability tables for locating elliptical targets with various borehole grid configurations have been published by Savinskii (1965) and Singer and Wickman (1969). These borehole grid tables give the probability of detecting a target given that the target exists at the site. The tables developed by Savinskii give the probabilities of locating underground elliptical targets with rectangular borehole grids for two cases, where the orientation of the target is known within ± 30 deg and where the orientation of the target is unknown or random. The shapes of the targets considered range from a circle to an ellipse with a ratio of the minor axis to the major axis of 0.10, which allows a wide range of target types, including solution caves, solution channels, and tunnels. Savinskii includes with the tables a series of nomograms that assist in the determination of the most efficient rectangular grid spacing for a given target shape and desired probability of detection. Three of these nomograms are presented here, for the cases in which (a) the target is circular (target obliquity, b' , is 1.0); (b) the target obliquity is 0.2 and the orientation unknown ($\theta = \pm 90$ deg); and (c) the target obliquity is 0.2 and the orientation is known within ± 30 deg. Figure 3.4 defines the variables



a. TARGET AND SEARCH GRID



b. NOMOGRAMS

Figure 3.4. Definition of the variables used in Figures 3.5 to 3.7 (After Savinskii, 1965)

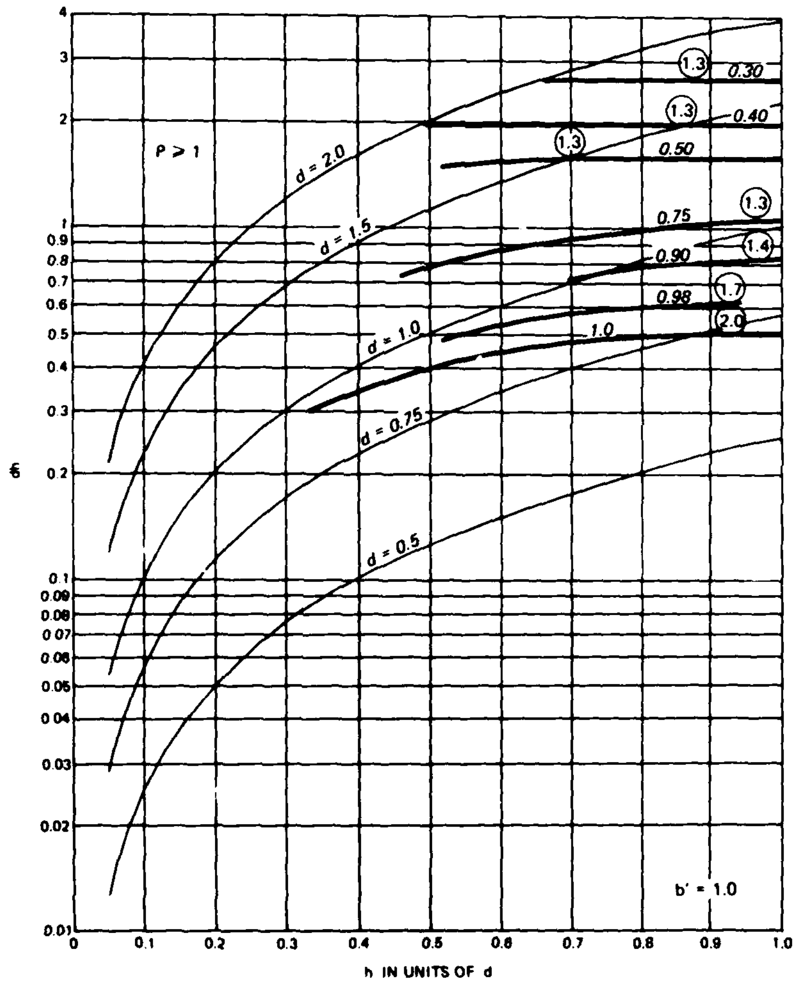


Figure 3.5. Borehole spacing nomogram for circular targets (b'=1.0)
(After Savinskii, 1965)

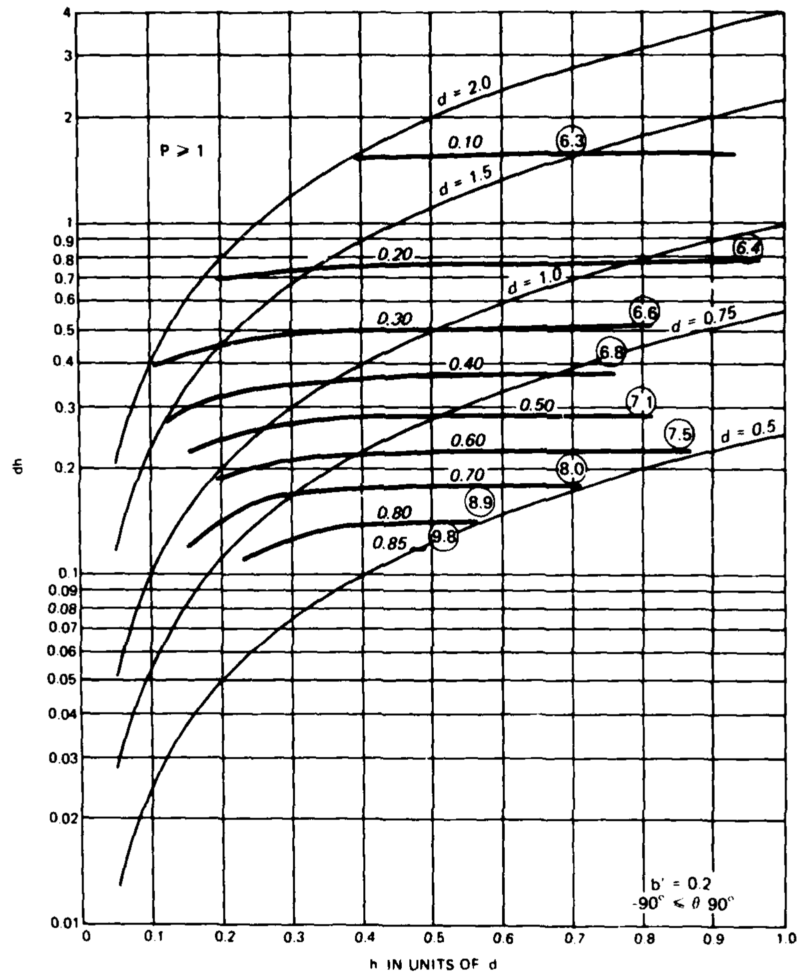


Figure 3.6. Borehole spacing nomogram for elliptical targets (b'=0.2) with unknown orientation (After Savinskii, 1965)

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FOUNDATION CONSIDERATIONS IN SITING OF NUCLEAR FACILITIES IN KA--ETC(U)
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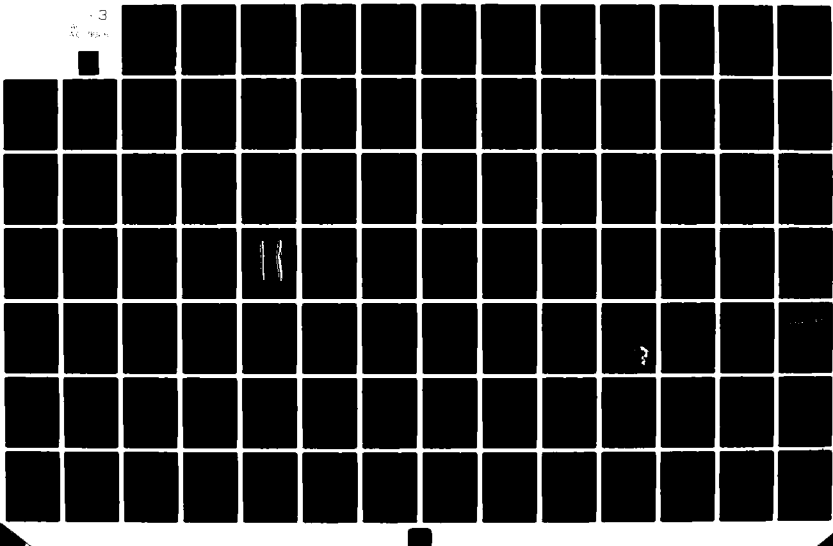

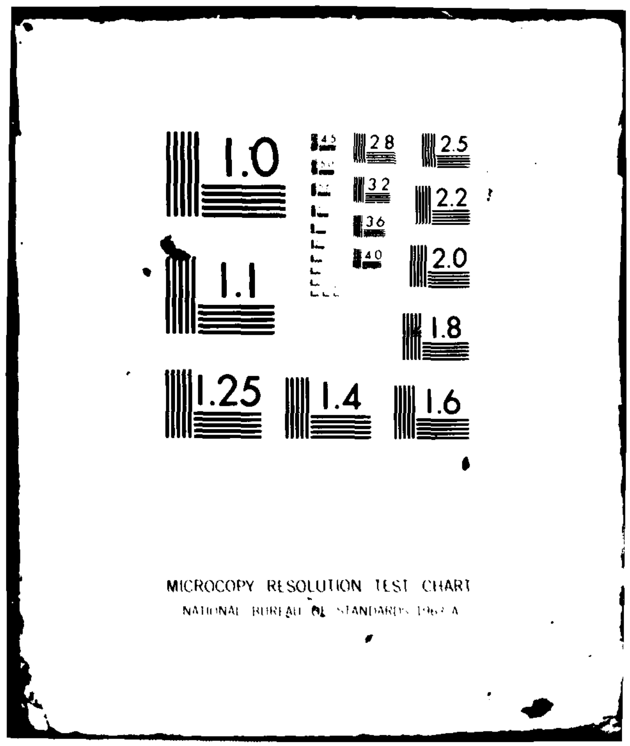
1.0
1.1
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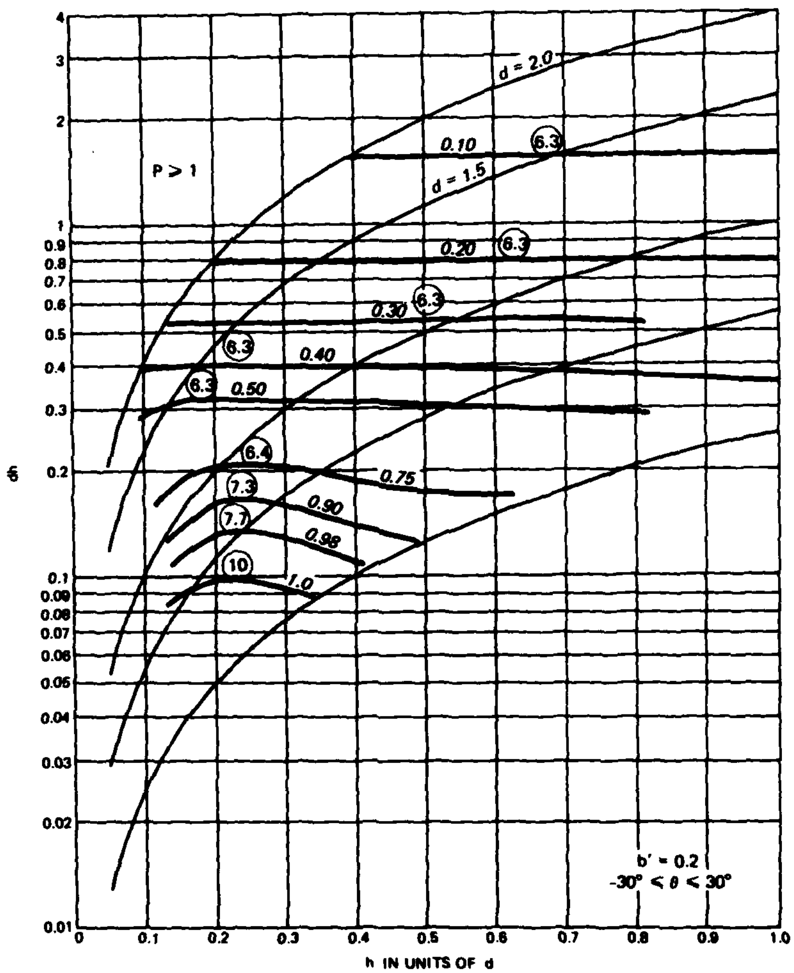


Figure 3.7. Borehole spacing nomogram for elliptical targets (b=0.2) with orientation known (± 30 deg) (After Savinskii, 1965)

used in the nomograms, Figure 3.5 is the borehole spacing nomogram for circular targets, Figure 3.6 is the nomogram for the case in which the orientation of the target is random and target obliquity is 0.2, and Figure 3.7 is the nomogram for locating targets of known orientation (within ± 30 deg) and target obliquity of 0.2. The nomograms give contours of constant probability of detection, P , and contours of constant borehole spacing in the x direction, d , on a plot of d • h versus h , where h is the borehole spacing in the y direction. The most efficient d, h combination for a specific level of P is the highest point on the corresponding P contour. For example, if a target has a minor axis of 2 metres and a major axis of 10 metres and the orientation is unknown, Figure 3.6 gives the nomogram for this shape and orientation of target. If the desired probability of detection is 0.80, the most efficient borehole plan (the fewest boreholes required) gives d = 0.5 and h = 0.56 , where d is in units of the length of the major axis and h is in units of d . So, for this example, the spacing between boreholes in the x direction will be 0.5 × 10 metres, or 5 metres, and along the y direction, the spacing will be 0.56 × 5 metres, or 2.8 metres.

If the orientation of this target is known within ± 30 deg, Figure 3.7 gives the corresponding nomogram. For a detection probability of 0.80, the most efficient d , h combination is d = 0.9 and h = 0.24. The distance between boreholes in the x direction will be 0.9 × 10 metres or 9 metres and the spacing in the y direction will be 9 × 0.24 metres or 2.16 metres. These two borehole grids are shown in Figure 3.8. For a total searched area of 350 m^2, the number of boreholes required to obtain a detection probability of 0.80 is 25 if the orientation is unknown and 18 if the orientation is known within ± 30 deg.

In the development of these nomograms, Savinskii found that if the orientation of the target is known, the axis of the largest borehole spacing (in this case the x axis) should be aligned with the semimajor axis of the target. The probability of detecting more than one target or targets of several different sizes can be determined from Savinskii's

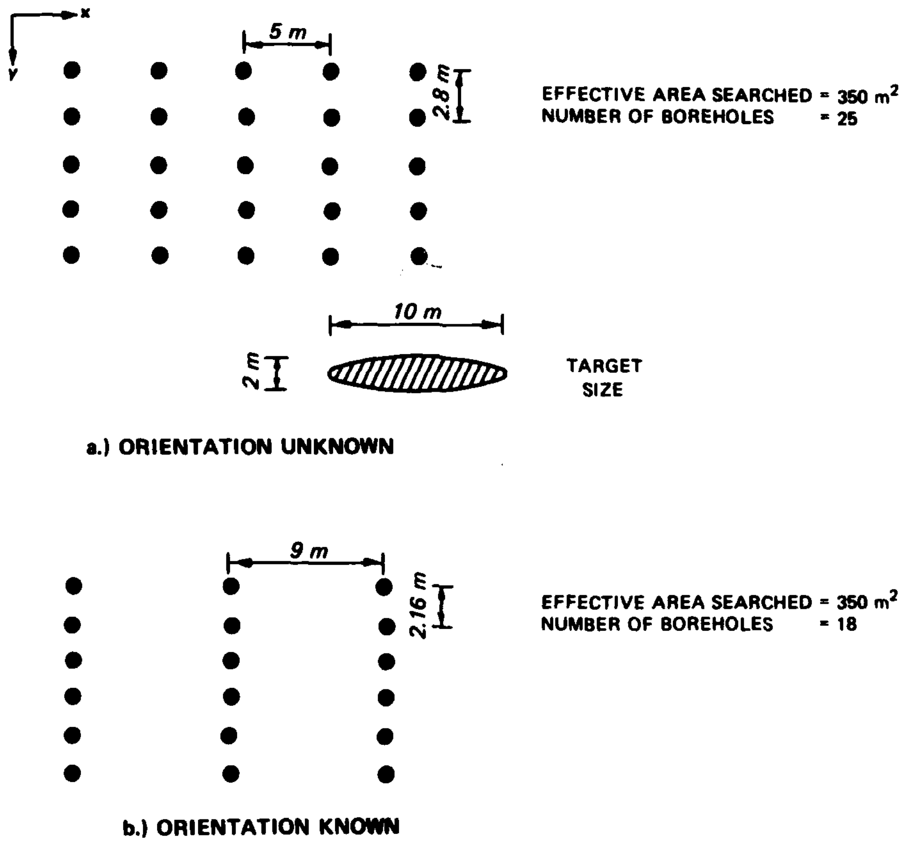


Figure 3.8. Most efficient borehole grids for 80 percent probability of detection

tables as long as the location and size of any one target is assumed to be independent of the location and size of any other target.

The work of Savinskii was extended by Singer and Wickman to allow specific target orientation for square, rectangular, and hexagonal borehole grids. A trial-and-error process is necessary to determine the most efficient borehole layout from the Singer and Wickman tables.

In 1976, Singer published a short (200 steps) FORTRAN computer program called RESIN for mapping the area proved by drill holes with respect to circular or elliptical targets of specified size and shape.

This program can be used to plot the areas at a site which have been adequately investigated by a previous exploration effort in order to assist the planning of additional exploration efforts.

In summary, two issues of strategy can be derived from the tabulated results (Baecher, 1978):

a. The orientation of the long axis of a rectangular grid that maximizes the probability of finding a target is parallel to the preferred orientation of the long axis of the target.

b. The grid obliquity that maximizes the probability of finding an oblique target is approximately equal to the target obliquity.

Inferences from Uniform Search

The probabilities discussed up to this point have described the likelihood of detecting a target with a specific borehole grid given that one target exists at the site. The probability of the existence of a target at the site (prior to the borehole investigation) may be estimated subjectively based on knowledge of the geology of the area. If no target has been found after the boreholes have been drilled, this prior probability can be updated by means of Bayes's Theorem. The posterior probability, P', that a target exists at the site, given no target was found with grid spacing (d, h) is as follows:

$$P' = \frac{P_o P[\text{no find} \mid (d, h), \text{target exists}]}{P_o P[\text{no find} \mid (d, h) \text{ target exists}] + (1 - P_o) P[\text{no find} \mid (d,h), \text{no target}]} \quad (3\text{-}4)$$

$$= \frac{P_o P[\text{no find} \mid (d, h), \text{target exists}]}{P_o P[\text{no find} \mid (d, h) \text{ target exists}] + (1 - P_o)(1.0)} \quad (3\text{-}5)$$

where P_o is the prior, perhaps subjective, estimate of the probability that a target exists at the site, and the conditional probability $P[\text{no find} \mid (d, h) \text{ target exists}]$ can be obtained from the borehole grid tables.

A more realistic problem might be to estimate the number of targets that remain undetected after a borehole program is complete. With the present level of development of probabilistic approaches in this topic, it is necessary to assume that the location of any one target is independent of the location of any other target. With these assumptions, the number of targets can be modeled mathematically with the Poisson distribution. This has been done by many researchers including Baecher (1978) and Lilly (1976).

The probability that n targets exist within a site of area A_s which is located within a region that has an average frequency of targets denoted by λ, which has units of targets per area, is given by the following:

$$P(n) = \frac{(\lambda A_s)^n \, e^{-\lambda A_s}}{n!} \qquad (3\text{-}6)$$

The parameter λ may be estimated, albeit subjectively, from aerial photographs, local geology, and other regional information. If it is assumed that no two targets overlap, then the probability of finding m targets with grid spacing (d, h) where n exist is given by:

$$P\left[\text{find } m \text{ targets} \,\middle|\, n \text{ exist, } (d, h)\right] \qquad (3\text{-}7)$$

$$= \frac{n!}{m!(n-m)!} \left(P\left[\text{find} \,\middle|\, (d, h)\right]\right)^m \left(1 - P\left[\text{find} \,\middle|\, (d, h)\right]\right)^{n-m}$$

where $P\left[\text{find} \,\middle|\, (d, h)\right]$ is given in the borehole grid tables for a single target.

The posterior probability $P'(n)$ that there are n targets at the site given that the borehole program has located m targets is calculated as follows:

$$P'(n) = \frac{P(n)\, P\left[\text{find } m \,\middle|\, n \text{ exist, } (d, h)\right]}{\sum_{i-m}^{k} P(i)\, P\left[m \text{ found} \,\middle|\, i \text{ exist, } (d, h)\right]} \qquad (3\text{-}8)$$

where $P(n)$ is calculated from Equation 3-6, $P\left[\text{find } m \mid n \text{ exist, } (d, h)\right]$ is given by Equation 3-7, and k is the maximum possible number of targets at the site. In order to maintain the Poisson form of the model, it is assumed that the higher order terms of the sum contribute very little and that k can be set equal to infinity. For example, suppose that the borehole spacing (d, h) is chosen such that the probability of locating an elliptical target with major and minor axes of (a, b) is 0.25; the area of the site $A_s = 1$ square mile, and $\lambda = \frac{16 \text{ targets}}{\text{sq mile}}$. The prior probability distribution for the number of targets at this hypothetical site is plotted in Figure 3.9. If the boreholes locate 6 targets, the probability of finding 6 targets given n exist, from Equation 3-7, is:

$$P\left[\text{find } 6 \mid n \text{ exist, } d, h\right] = \frac{n!}{6!(n-6!)} (0.25)^6 (1-0.25)^{n-6} \qquad (3\text{-}9)$$

The updated probability distribution $P'(n)$ of the number of targets at the site can be calculated by substituting into Equation 3-8 and simplifying:

$$P'(n) = \frac{P(n)\, P\left[\text{find } 6 \mid n \text{ exist, } P_{detect} = 0.25\right]}{\sum\limits_{i-6}^{\infty} P(i)\, P\left[6 \text{ found} \mid i \text{ exist, } P_{detect} = 0.25\right]}$$

$$\frac{\dfrac{(16)^n e^{-16}}{n!} \cdot \dfrac{n!}{6!(n-6)!} (0.25)^6 (1-0.25)^{n-6}}{\sum\limits_{i-6}^{\infty} \dfrac{i!}{6!(i-6)!} \cdot \dfrac{(16)^i e^{-16}}{k!} (0.25)^6 (1-0.25)^{i-6}} \qquad (3\text{-}10)$$

$$= \frac{(16 \times 0.25)^{n-6} e^{-(16 \times 0.25)}}{(n-6)!} \qquad (3\text{-}11)$$

This updated distribution is also plotted in Figure 3-9. Note that the posterior distribution is much narrower than the prior distribution.

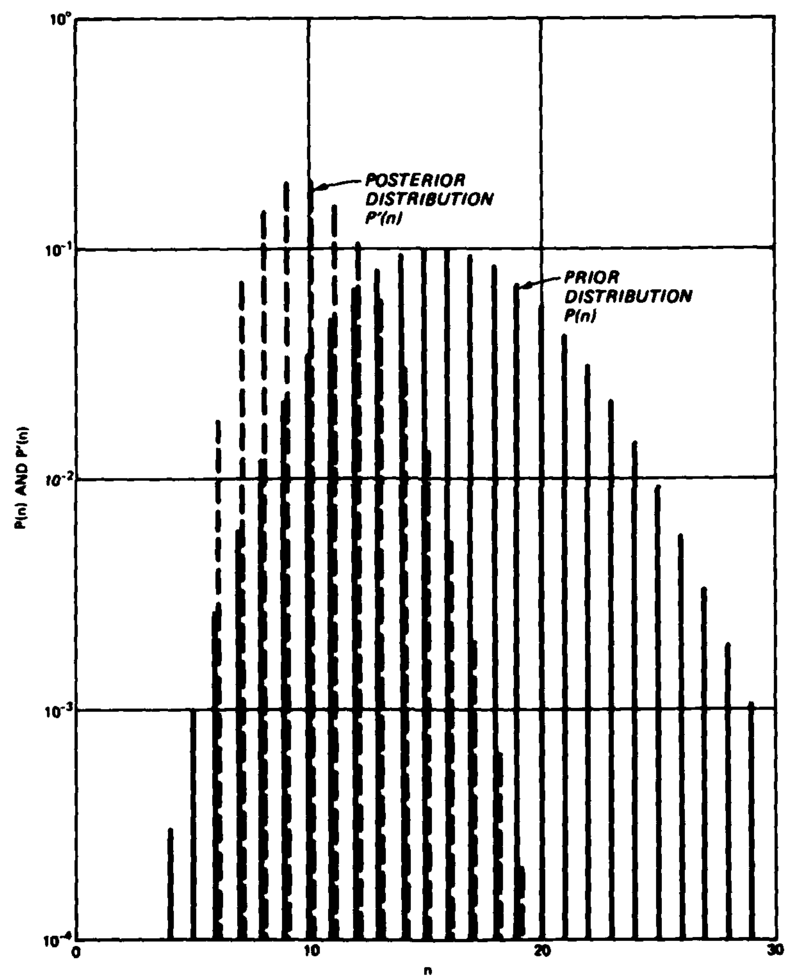


Figure 3.9. Prior and posterior probability distribution of target occurrence at a hypothetical site

This indicates that the drilling program has reduced the degree of uncertainty about the number of targets at the site.

The probability that there are no targets at the site is obtained by setting $n = 0$ in Equation 3-6:

$$P(0) = \frac{(\lambda A_s)^0 \, e^{-\lambda A_s}}{0!} \qquad (3\text{-}12)$$

The probability that one or more targets exist at the site would be 1 minus the probability of no targets:

$$P(n = 1 \text{ or more}) = 1 - e^{-\lambda A_s} \qquad (3\text{-}13)$$

In more general terms, the updated or posterior distribution on the total number of targets n at the site is still a Poisson distribution; however, the frequency λ is reduced by the probability of detection P for a particular borehole plan, and the value of n is reduced by the number of targets found, m :

Prior Distribution on Number of Targets, n

$$P(n) = \frac{(\lambda A_s)^n \, e^{-\lambda A_s}}{n!} \qquad (3\text{-}14)$$

Posterior Distribution for n after m Targets are Found

$$P'(n) = \frac{(P\lambda A_s)^{n-m} \, e^{-P\lambda A_s}}{(n-m)!} \qquad (3\text{-}15)$$

Multiple-Stage and Sequential Search

The investigation of a site suspected to be underlain by cavities would typically consist of more than one stage of exploration effort. For example, one or several geophysical techniques might be applied to indicate the location of anomalies, then boreholes would be drilled to verify the locations. Since geophysical methods are not perfect indicators of cavities and considerable judgment is required to extract information from the data, this stage of investigation may indicate the locations of some actual targets and also indicate targets where none exist. The probability distribution for the locations of targets would no longer be uniform over the site, but would now be adjusted to conform to the results of the geophysical investigation. This means that the aforementioned tables for borehole grids would not be applicable for describing the effectiveness of the drilling stage, since they require a uniform probability distribution of targets.

The structure of the exploration optimization problem in two stages is quite simple. If cost can be considered an adequate criterion, the objective is to minimize the total expected cost of the two-stage search. The costs to be included are: (a) the cost of the first stage of exploration, C_1 ; (b) the cost (or some measure of benefit) of finding a target, C_f ; (c) the cost of the second stage search, C_2 ; and (d) the cost of missing a target, C_M The total expected cost, $E[\text{cost}]$, is computed by Equation 3-16:

$$E[\text{cost}] = E[\text{number of targets found}]C_F - E[\text{number of targets missed}]C_M - C_1 - C_2 \tag{3-16}$$

The expected number of targets found and missed depends on (a) the probability distribution for the number of targets at the site and (b) the effectiveness of the search methods expressed as the probability of finding or missing a target. At this time, the probabilistic tools have not been developed and applied sufficiently to handle a real-world search problem. This is a topic now under research.

Similar problems of updating probability distributions occur in sequential search strategies. In the field of operations research, this would be referred to as a dynamic programming problem. A sequential search has several stages and the objective is to optimize the entire search process. The optimal strategy for the process is to make the best decision at each individual stage on the basis of all past information. The proof of this solution can be found in DeGroot (1970).

Optimal Nonuniform Search and Gradient Methods

The theory of optimal search for nonuniform prior probability distributions on target locations was developed by Koopman (1956a,b,c; 1957). The Koopman technique is a simple procedure for optimal allocation of a fixed level of exploration effort. For an example of the Koopman technique applied to aerial photographic study of a geological problem, see Baecher (1978). The solution to this optimization problem reduces to the simple result of putting more effort where the target is more likely to be located, and less effort where the probability distribution indicates the target is less likely to be.

Linear programming or gradient methods have been applied to mining problems by Wilde (1974) and Koch and Link (1971). The problem with these methods is that they are limited to a single target and cannot adequately handle prior probability distributions of target locations that are multimodal.

Random Process Models

A few researchers (Vanmarcke, 1977); Veneziano et al., 1977) have begun to deal with periodic variations of soil properties or profiles. Vanmarcke (1979) has designed a search strategy for estimating average soil properties and their variations along horizontal and vertical directions. This technique is similar to the work of Veneziano et al. (1977) who have applied three-dimensional random process techniques to estimate volumes of mineral deposits that remain in the ground weighed against the value of continued mining. The theory being developed by these researchers may be applicable to cavity detection problems in the future.

CHAPTER IV: SITE INVESTIGATIONS - GEOPHYSICAL METHODS

CHARACTERISTICS OF GEOPHYSICAL METHODS

As a background to the discussion of geophysical methods, it is helpful to consider some general observations made by Schmidt, el al (1976):

"(1) Geophysical surveys utilize both active and passive measurement techniques. In an active mode, some form of energy is introduced into the subsurface and the effect on the energy or the response of subsurface materials to energization is measured. Active measurement techniques usually provide the greatest accuracy. Passive measurements simply record the strengths of various fields or changes in field strength which are always present. Analytical assumptions that introduce ambiguity in the results are necessary for interpretation.

"(2) Precision of measurements is high in all methods, but accuracy in the interpretation and inferences drawn from the measurements depends very much on the experience of the interpreter. All methods are inherently subject to lower accuracy due to interpretation as distance increases between the energy or field source of interest and the detecting sensors, especially in those methods based on field strength measurements (passive mode).

"(3) Resolution capability of subsurface characteristics varies widely among the geophysical methods when surveys are conducted conventionally. The parameter to be measured or inferred must be understood before a resolution dimension can be defined. Almost total resolution of any soil or strata parameter is possible if the survey is appropriately designed and time/cost requirements are not considered. One reasonable approximation is selection of measurement point separation on the order of the dimension of objects or strata changes to be resolved.

"(4) Very few geophysical methods measure parameters directly used by the engineer (seismic and electrical methods may be exceptions), and all methods present the 'averaged' effects of materials between and around sources and points of observation. Most results are based on interpretations that infer what kind of conditions would cause the measured parameter to have a certain value or to change in a certain way."

As a further caveat, it should be noted that the interpretation of geophysical data is based on the assumptions that the various earth materials have distinct subsurface boundaries and are both homogeneous and isotropic. These assumptions are in many cases at variance with reality.

There is no substitute for direct evidence of ground conditions as determined by borings and excavations, and any geophysical survey should be planned with this in mind. Borings or excavations should be used in conjunction with geophysical explorations in order to validate geophysical interpretations (or if necessary to calibrate or correct them). If used in this manner, geophysical methods offer both economic advantages and the ability to rapidly explore large subsurface volumes with adequate accuracy.

RESPONSE OF GEOPHYSICAL MEASUREMENTS TO CAVITIES

Principles

Basically, the problem in geophysical site investigations in areas where cavities must be considered is the determination of the presence or absence of localized anomalous conditions and the subsequent delineation or detailed mapping by geophysical and drilling methods of any anomalous conditions found. The primary features of concern are cavities below the rock surface, which may occur in association with solution-widened joints produced by karst processes or with fractured rock zones, related to breakdown and collapse, extending to the surface. The geophysical anomaly produced by a cavity system will depend intimately on its size and the nature of the filling material (air, water, clay, or other secondary geologic material). In order to use geophysical methods for investigation of cavities, it is necessary to understand how the physical parameters measured by the various geophysical techniques are affected by (a) the presence of cavities, (b) their sizes, and (c) associated filling material.

The seismic wave propagation methods involve the measurements of transit times and wave signatures for energy propagation between pairs of points located so that the received energy must pass through or around the target. Seismic waves incident on air-, water-, or clay-filled cavities will, in nearly all cases of interest, exhibit greater transit times due to delays in passing through the filling materials or the longer travel paths involved in going around the cavities. Also, the amplitudes will exhibit characteristic signatures due to diffraction caused by the cavities. Seismic refraction and crosshole seismic methods are designed to detect anomalies of these kinds. Reflection methods, on the other hand, use sources and receivers placed close together so that the received energy must be reflected from the target. For seismic wavelengths smaller than the characteristic sizes of the cavities, air- and water-filled cavities are good reflectors of incident seismic waves; and indeed, for air-filled cavities, the amplitude of reflected waves in an idealized plane geometry (plane waves incident on an air-filled half-space) is essentially equal to the amplitude of the incident waves. Thus, in principle, a cavity, particularly an empty one, should produce a detectable localized reflection event on seismic reflection records. These same concepts hold for electromagnetic (EM) wave transmission and reflection methods, except that the air-filled cavity will result in a decreased travel-time anomaly due to the greater propagation velocity in air.

Gravity methods make use of the fact that for nearly every conceivable situation, the air-, water-, or clay-filled cavity represents a negative density contrast (i.e., the filling material has a lower density than the surrounding rock). This negative density contrast will result in a decreased gravitational attraction on the surface above the cavity, which can be detected by a sensitive gravity meter. For practical application in engineering surveys, a microgravimeter, having a sensitivity of about 10^{-9} times earth gravity, is required.

Electric currents in the ground will be perturbed by the presence of a cavity, deflected around an air-filled cavity but generally preferentially concentrated in water- and clay-filled cavities due to the associated negative and positive conductivity contrasts of the cavity relative to the surrounding medium. Surface resistivity methods depend on measuring electrical potential differences produced by applied electric currents from which are computed apparent resistivity values. The deflections of current described above will usually result in relatively high apparent resistivity values above air-filled cavities and relatively low apparent resistivity values above water- or clay-filled cavities.

The objective of the magnetic methods is the discovery of relative highs and lows of the magnetic field on the surface, which reflect variations in the magnetic susceptibility of material in the subsurface. Generally, the susceptibilities of sedimentary materials in a karst environment will be rather low; however, the clay in-filling materials of a cavity can have a susceptibility larger by a factor of two than the host carbonate rock. Thus, a concentration of magnetic flux lines through a clay-filled cavity will produce a magnetic high on the surface, although it may be small. An air- or water-filled cavity in carbonate will generally have a negligible or imperceptible effect on the magnetic field. In the case of mines, which may occur in rocks with considerably larger susceptibilities, the presence of metallic objects and brick lining materials could result in significant magnetic anomalies. Because magnetic methods are not believed to be generally useful for cavity detection in karst environments, they will not be discussed at length in this report. A discussion of the theory of magnetic surveying, as applied to cave detection, and examples of surveys over known caves, are given by Lange (1965). According to Lange, cavities in lavas, which frequently have high magnetite content, are most amenable to magnetic detection, while cavities in soluble rocks are likely to produce no resolvable anomalies.

Past Cavity Detection Efforts

All of the geophysical principles mentioned above have been used in attempts to detect and delineate cavity systems, and the opinions of how best to proceed in a cavity detection program are widely varied. Some interesting trends emerge when publications on cavity detection are reviewed. In the United States the ranking of geophysical methods, in terms of numbers of publications and stated preferences of researchers, seems to be (a) seismic methods, (b) resistivity and EM methods, and (c) gravimetric methods. In Europe, a similar ranking of methods would be somewhat different: (a) gravimetric methods, (b) resistivity and EM methods, and (c) seismic methods.

As with any geophysical exploration effort, no single method should be relied on to give the best geophysical picture of subsurface conditions in a site investigation for cavities; the most effective site investigation would use a combination of complementary methods. The following paragraphs briefly review geophysical methods that have been applied to the cavity detection problem and suggest rational geophysical site investigation methodologies tailored to the motivation and stage in the overall site investigation program.

Seismic Methods

Refraction

The application of standard seismic refraction methods (see e.g., U. S. Army, 1979a; Telford, et al, 1976) to detection of cavities has met with only limited success, and its usefulness for this purpose is questionable except in special situations (Love, 1967; Brooke and Brown, 1975; Rat, 1977; Frappa, et al., 1977; Burton and Maton, 1975; Bates, 1973; Schepers, 1975; and Butler and Murphy, 1980). Since the standard refraction method uses an in-line profiling geometry, the trend of the cavity must cross the profile line and intercept one or more possible seismic ray paths to the geophones in order to offer a possibility of detection. In addition, the effective seismic wavelength should be of the same order or smaller than the characteristic size of the cavity in order for the cavity to be "seen" by the refraction method; this would require producing and preserving frequencies in the 500-2000 Hz range for small cavities in limestone, which is beyond the capability of most standard refraction systems.

The geometric problems with seismic refraction for cavity detection are multiplied by the nature of the refraction process itself. Figure 4.1 illustrates, in a hypothetical fashion, the nature of the problem. Consider three cavities in a two-layer medium in which the deeper layer has a higher P-wave velocity, and a refraction line as shown, and assume that the cavity size is sufficiently large to affect detectably seismic energy incident on it. Cavity 1 would produce no effect on the refraction first-arrival time-distance plot. However, if cavity 1 were located to the left, intercepting the critically incident ray, all refracted arrivals would be uniformly delayed, producing an erroneously large computed depth to the interface but no observable cavity "signature." Cavity 2 would produce arrival time delays at geophones 7, 8, and 9, and hence would be detectable. Cavity 3 would cause no effect whatever at the geophone locations, unless a second refractor were located below the cavity at a shallow enough depth to produce first arrivals at some of the geophone locations. Cavity 3 represents a common situation, in which

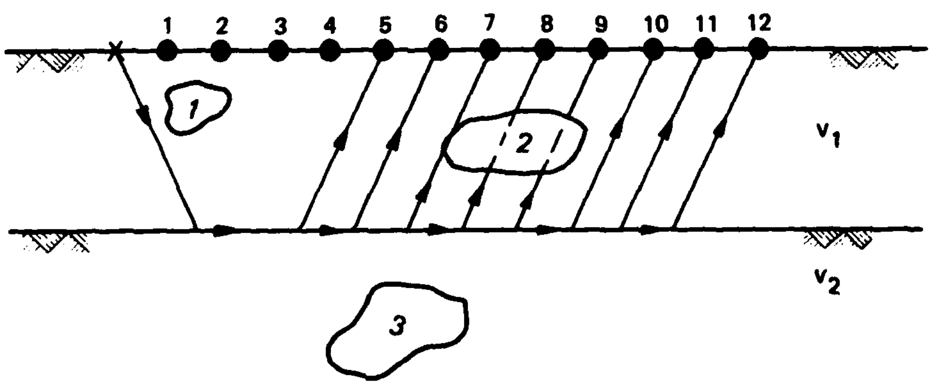


Figure 4.1. Hypothetical seismic refraction survey line over subsurface with three cavities ($V_2 > V_1$)

layer 1 is a soil cover and layer 2 is a carbonate rock, for which cavity detection by standard seismic refraction is not very promising.

In the real world, however, the assumptions of this hypothetical example are violated in several ways. The direct arrivals penetrate layer 1 to some extent, following curved paths due to increases in velocity with depth in the layer. Real cavities are always accompanied by surrounding zones of altered material properties due to cracking and solution effects. The altered zones can substantially increase the physical size of the zone that will affect propagation times and characteristic signatures. Consequently, refraction seismic techniques can, under certain circumstances, be used effectively for the detection of cavities.

For cases where solution cavities (such as 3 in Figure 4.1) are shallow with respect to the top of rock, the zones of increased porosity due to solution around the cavity may extend to the top of the rock and even influence preferred drainage paths and weathering in the overlying soil material. For these cases, standard seismic refraction can be of use in mapping such altered rock zones under a soil cover (Curro, et al, 1980). However, the first-arrival time-distance plots will often be very complex and not easy to interpret in terms of cause and effect.

A modified seismic refraction technique referred to as a constant spacing refraction survey has recently been effectively used in karst areas (Curro, et al., 1980). The procedure uses a source and single receiver which are maintained at a constant spacing throughout the survey. The source and receiver are moved along profile lines in equal increments, with the spacing typically being about 15 m and the increments about 1.5 to 5 m. At each location, the seismic records are examined for wave-form character (frequency content, amplitude, etc.) and arrival time. Low frequencies, low amplitudes, and/or delayed arrival times relative to other locations are taken to be indicative of anomalous conditions in the subsurface. The method is quick and easy to perform in the field and can be interpreted qualitatively onsite.

Various parameters can be extracted from the records, such as maximum amplitude, dominant frequency, and arrival time; and, since the data are collected on profile and grid patterns, they can be assigned to the centers of their respective source-receiver locations and plotted or contoured.

Reflection

The fact that air- or water-filled cavities should be good reflectors of seismic energy has long been appreciated. Cook (1965) demonstrated experimentally that cavities in salt could be detected by reflection. However, the cavities were quite large and deep (300-500 m depth) compared to most underground openings of interest in engineering site investigations. For detection of shallow cavities, high-resolution, high-frequency seismic reflection methods are discussed by Owen and Darilek (1977), Fountain and Owen (1967), Frappa, et al., (1977), and Rechtien, et al., (1976). Figure 4.2a illustrates the field layout used by Owen and Darilek (1977) for detection of a solution cavity in limestone at a depth of about 45 m, and Figure 4.2b illustrates the hypothetical response expected from a cavity target and planar target. The results of the actual survey by Owen and Darilek (Figure 4.3), while suggestive of the presence of the cavity, probably would not have led to its discovery if its presence had been unknown. Also, a field procedure such as illustrated in Figure 4.2a would not be time- or cost-effective for engineering site investigations.

Rechtien, et al., (1976) explored the possibility that high amplitude, low-frequency events occurring late on seismic reflection records obtained over limestone caverns were due to surface-wave interactions with the cavities. They concluded that seismic detection of cavities is possible, but that instrumentation requirements and the close geophone spacings required prohibit its use as a reconnaissance tool. An attempt by Butler and Murphy (1980) at preliminary application of a simple field seismic reflection procedure for cavity detection was largely unsuccessful, although a simple, single channel, vertical seismic reflection profiling procedure reported by Howell and Amos (1975) seemed to detect buried

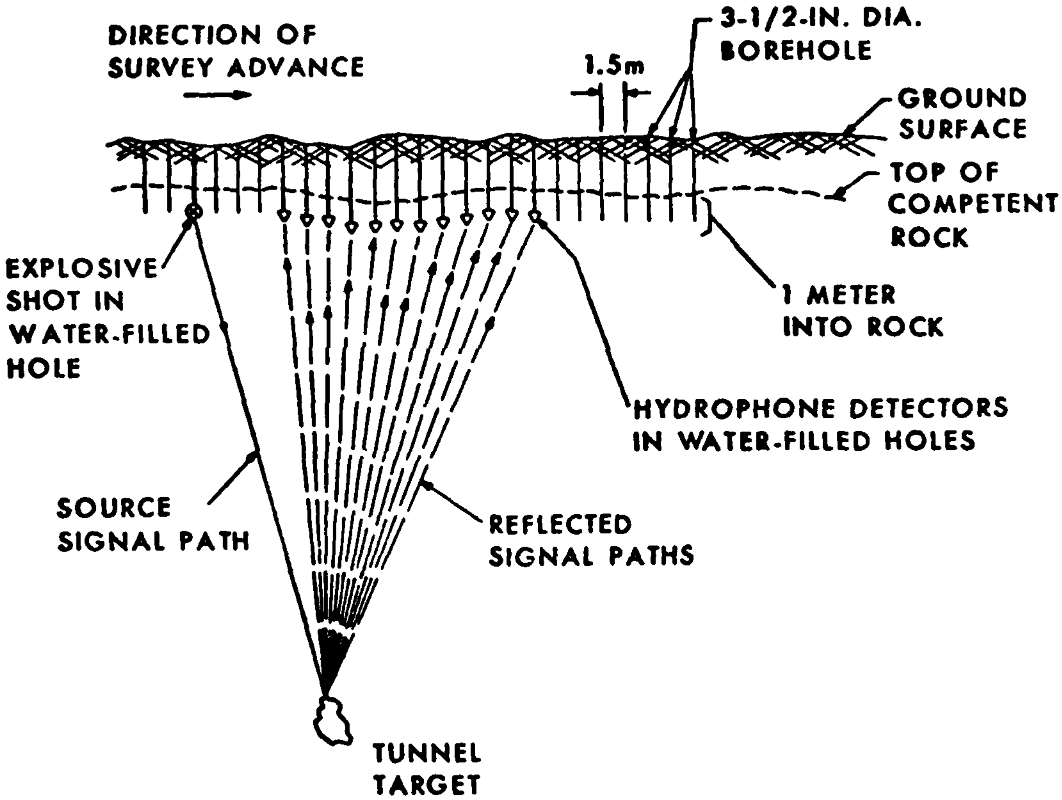


Figure 4.2a. Field layout for high-resolution seismic reflection survey for tunnel detection. (Owen and Darilek, 1977)

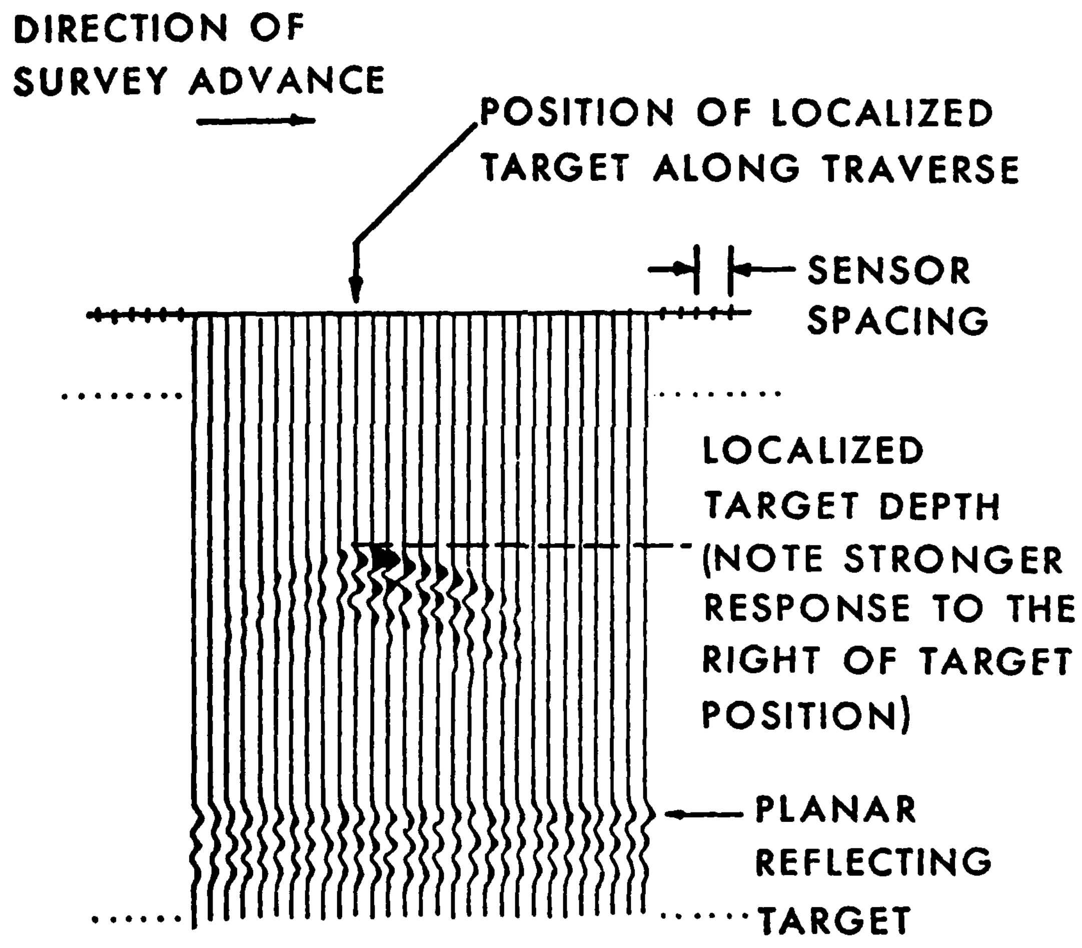


Figure 4.2b. Common depth point display representation for localized and planar targets. (Owen and Darilek, 1977)

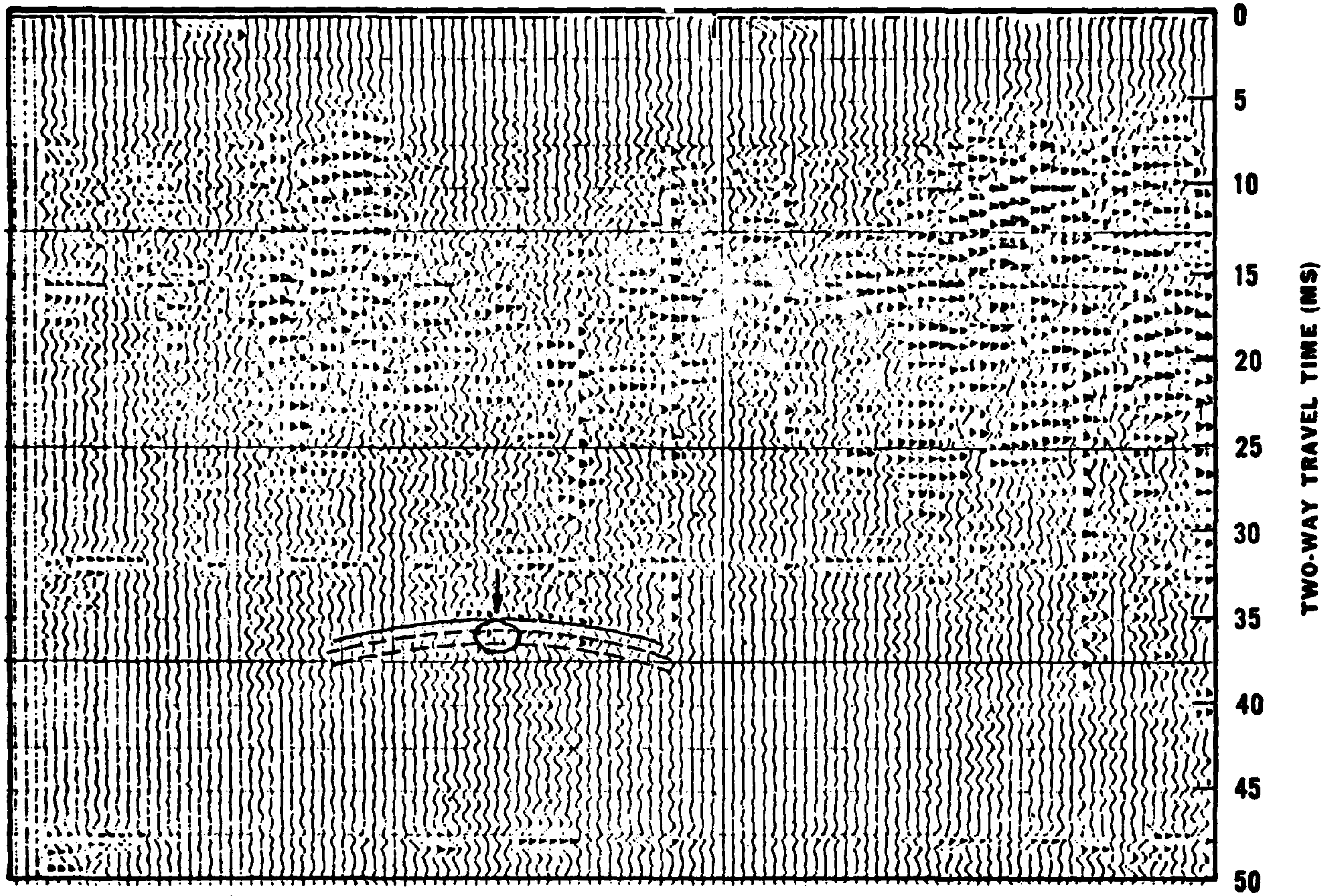


Figure 4.3. High-resolution seismic reflection survey results over solution cavity. (Owen and Darilek, 1977)

mine openings. The seismic reflection in-line profiling method suffers from the same geometric problems as discussed for the refraction method and the detection of reflections from very shallow cavities (less than 15 m) is hindered by interference from large surface-wave arrivals. High-frequency, high-resolution seismic reflection techniques using pseudorandom and coded seismic sources and sophisticated data processing techniques have been successfully applied to the detection of cavities at 50 m depth and below, and may have application to cavity detection at lesser depths in the future (Schepers, 1974; Serres and Wiles, 1978; Barbier, et al, 1976). These techniques, however, may not become cost-effective for site investigations for some time and likely will not prove to be useful for very shallow depths (less than 15 m).

Fan shooting

Seismic fan shooting is basically a refraction method, but the shot or source point is not in line with the receivers. The receivers are commonly arranged along a circular arc with the shotpoint at the center of the arc. The method was successful in the detection of salt domes in the 1920's and 1930's (McGee and Palmer, 1967). Salt domes represent large localized targets for seismic methods. The adaptation of fan-shooting techniques for small localized targets, which is the case in cavity detection, is a possibility which has not been adequately explored, but the work of Elliot (1967) and Waboso and Mereu (1978) on applications of fan shooting to shallow, localized ore body delineation seems directly applicable (the work by Elliot involved low velocity sulfide deposits imbedded in Precambrian basement rocks). Simple broad-side fan shooting has been used with some success in karst areas in Alabama (Newton, et al., 1972), and Curro (1981) used the circular arc fan geometry in field studies at a cavity test site in Florida. Figure 4.4a shows the test plan used by Curro, where the axis of the fan is approximately along the known trend of a cavity system; and Figure 4.4b illustrates the results of one of the fan tests. The first-arrival time anomalies at geophones 1, 10, and 11 are due apparently to previously known cavities at the site, while the anomalies at geophones 23 and 24 result from a cavity discovered during exploratory drilling at

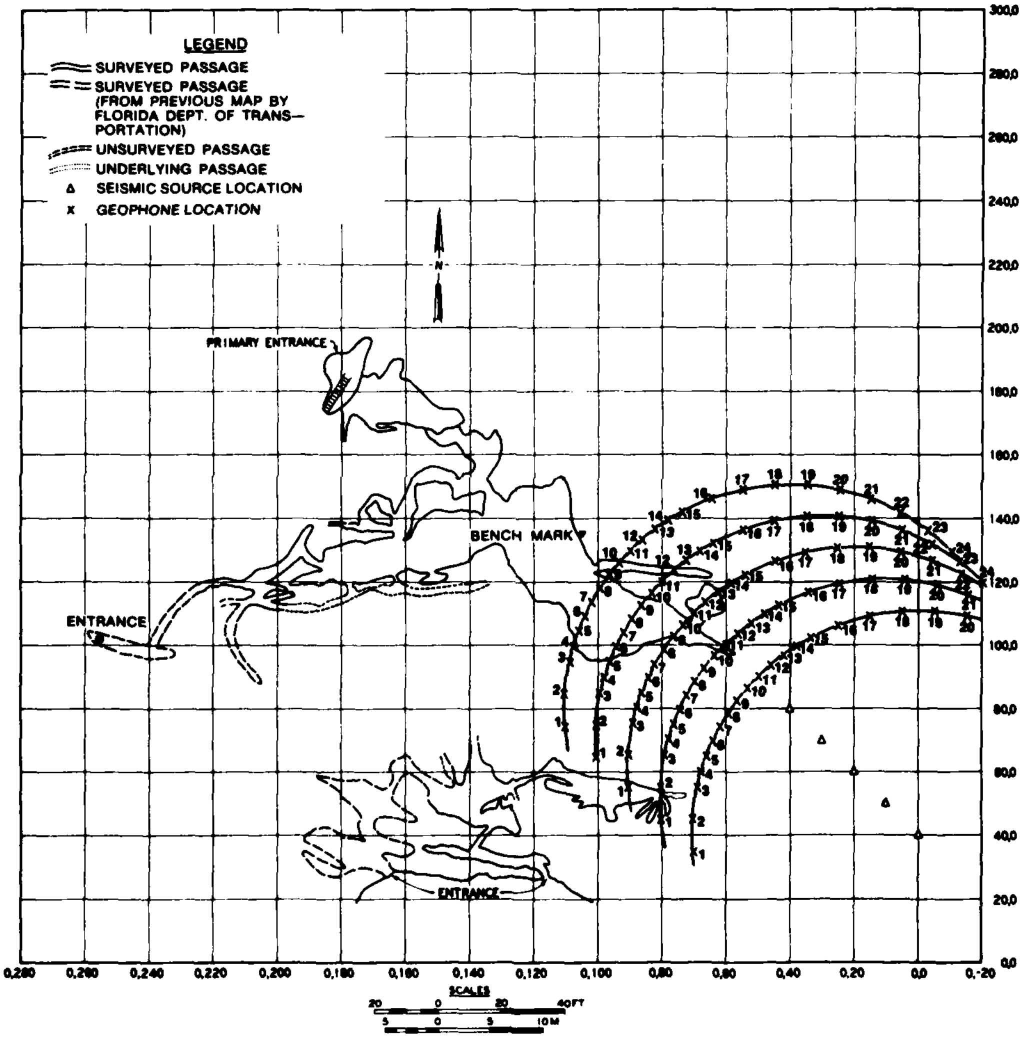


Figure 4.4a. Seismic fan test geometry at Medford Cave, Florida, test site

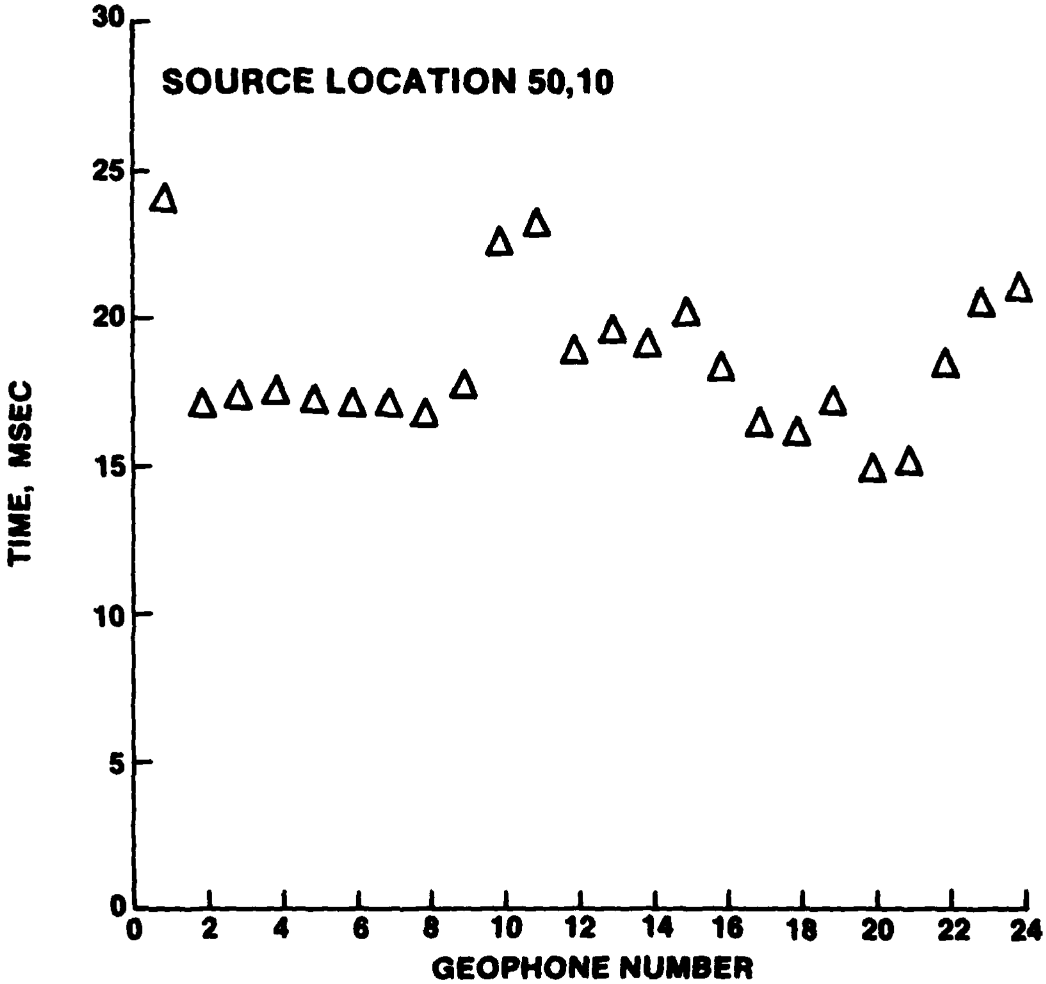


Figure 4.4b. Fan-shooting test results at Medford Cave site

the site. The use of an expanding fan as suggested by Butler and Murphy (1980) would, in principle, allow not only the mapping of anomalous zones at a site but also give an indication of depth of the anomaly. While fan-shooting techniques overcome some of the geometric limitations of in-line refraction methods and allow areal coverage of a site, all of the other limitations discussed still apply.

Subsurface seismic methods

Subsurface seismic methods applicable to cavity detection include crosshole seismic techniques and uphole refraction. In the crosshole seismic technique, both the source and receiver are in boreholes, and both explosive and polarized shear-wave sources (vibrators and hammers) are used, as well as such impulsive sources as air guns and sparkers. The crosshole technique has been used extensively for site investigations in which the objective is the determination of compression and shear-wave velocities to be used in computations of dynamic response of foundations (Curro and Marcuson, 1978 , for example). Clearly, for cavity detection applications, the cavity must lie between the source and receiver boreholes. In order for the interpretation of shallow crosshole tests to give true velocities and to detect the presence of cavities between the boreholes, relatively close borehole spacings, say 6 to 10 m, are required (Butler, et al., 1978). Some workers report the successful detection of cavities using boreholes separated by as much as 23 m. For such large borehole separations, cavities or anomalous low density zones (due to solution) must also be rather large in order to be detected. Whatever the borehole spacing used, interpretation of the results requires consideration of the possible refraction of the first-arrivals through high-velocity zones (Butler, et al., 1978). While the previous comments on seismic wavelength and cavity size still hold, the crosshole geometry, close proximity of source to receiver, and (for test locations below top of rock) the absence of an energy-absorbing soil medium between source and receiver make the crosshole method a very attractive candidate for cavity detection (Butler and Murphy, 1980; Curro et al., 1980; Grainger and McCann, 1977;

Dresen, 1973; Millet and Moorhouse, 1973). The test geometry is illustrated schematically in Figure 4.5a. Figure 4.5b presents the interpreted results of a crosshole test at a natural cavity site, showing reduced compression-wave (P-wave) velocities at depths corresponding to the mapped depths of a known cavity. Use of sources producing vertically and horizontally polarized signals with controlled wave-form enhances the possibility of cavity detection (Butler and Murphy, 1980) and reported results are encouraging. Figure 4.5c shows the changes in wave form (primarily in amplitude) resulting from interaction of vertically polarized shear waves with a man-made cavity in soil. Due to the need for closely spaced boreholes, the crosshole method would most likely be of use for detailed investigations in the later stages of a site investigation, particularly for obtaining information between boreholes in a systematic site drilling program.

The uphole refraction technique uses an array of surface geophones, along a line extending away from the borehole, with a seismic source in the borehole. Typically the source is positioned at several successive elevations in the borehole and records are obtained for each elevation. Using this geometry, Meissner (1961) proposed a scheme for constructing wave-front diagrams from the first arrival time data. The Meissner technique has been applied to data obtained in karst regions in attempts to detect cavities, but interpretation of "wave-front diagrams" for such cases is not straight-forward nor is the wave-front analogy strictly valid (Franklin, 1977, 1980). However, some success is claimed by adherents of the method. In any event, the Meissner diagram is a convenient method of presentation of the data. Franklin (1980) demonstrates that if a Meissner diagram for a postulated simple layered subsurface is subtracted from the field Meissner diagram, to yield an <u>anomaly diagram</u>, it is sometimes possible to isolate and interpret the travel time anomalies due to cavities or other irregularities. However, the travel time anomalies even for rather large cavities, if isolated, will be small and may not be detectable with standard refraction equipment. On the other hand, a zone of fracture or intensified weathering extending

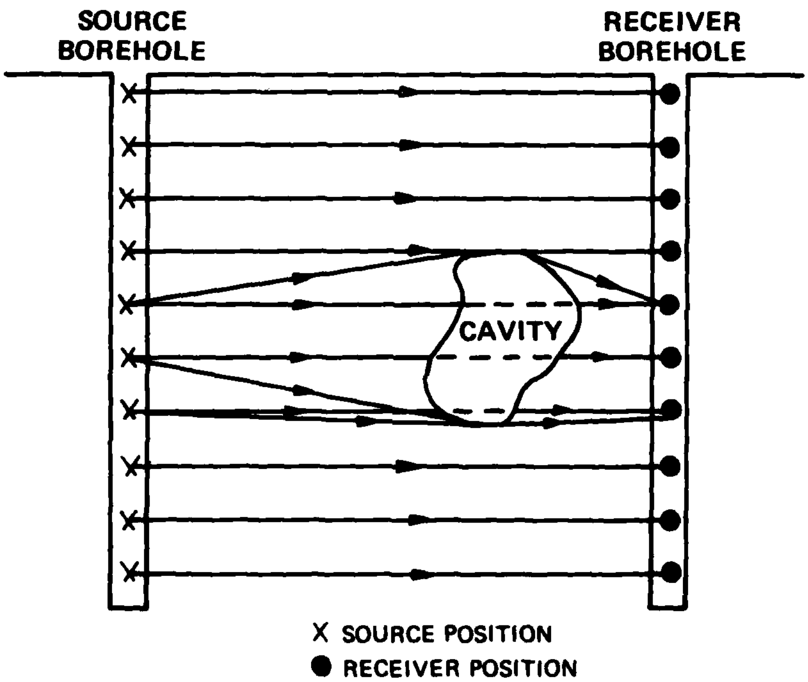


Figure 4.5a. Crosshole seismic test geometry

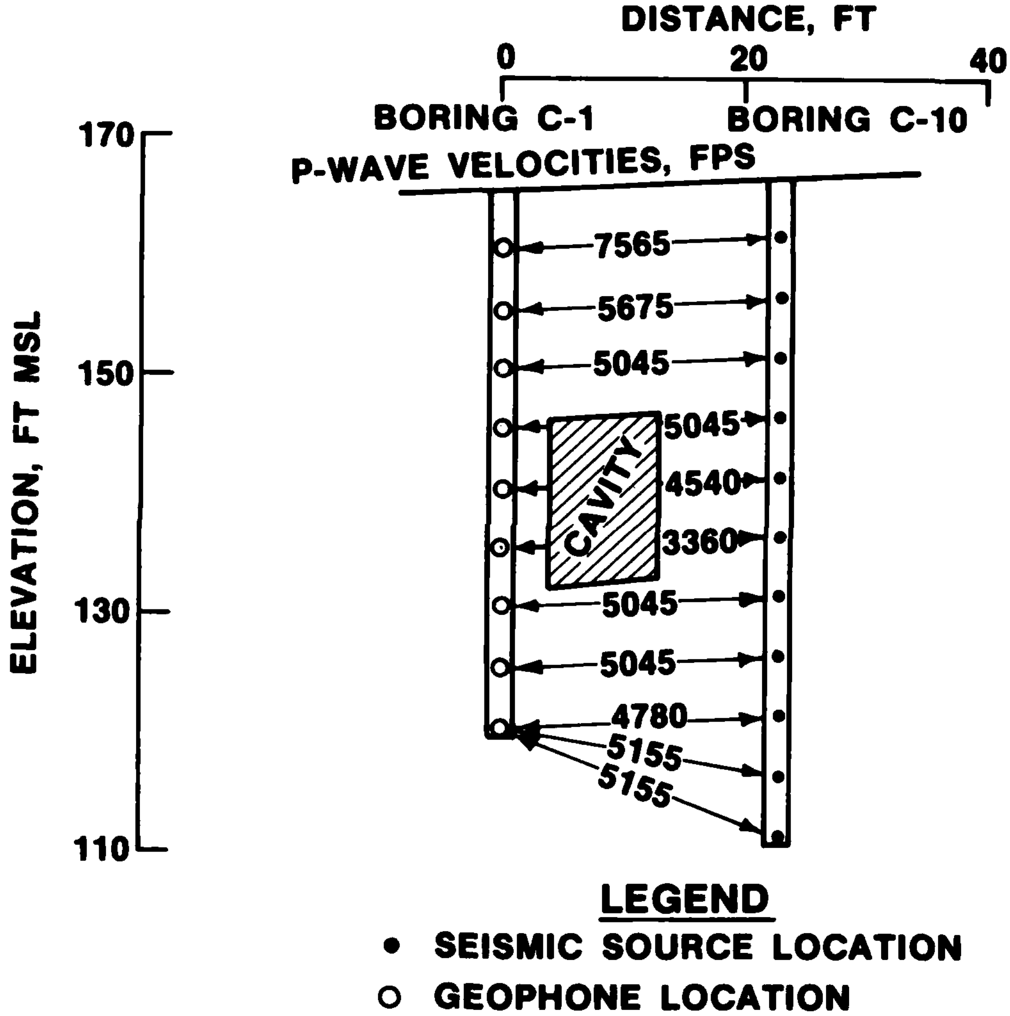


Figure 4.5b. Crosshole seismic test results at site with a natural cavity

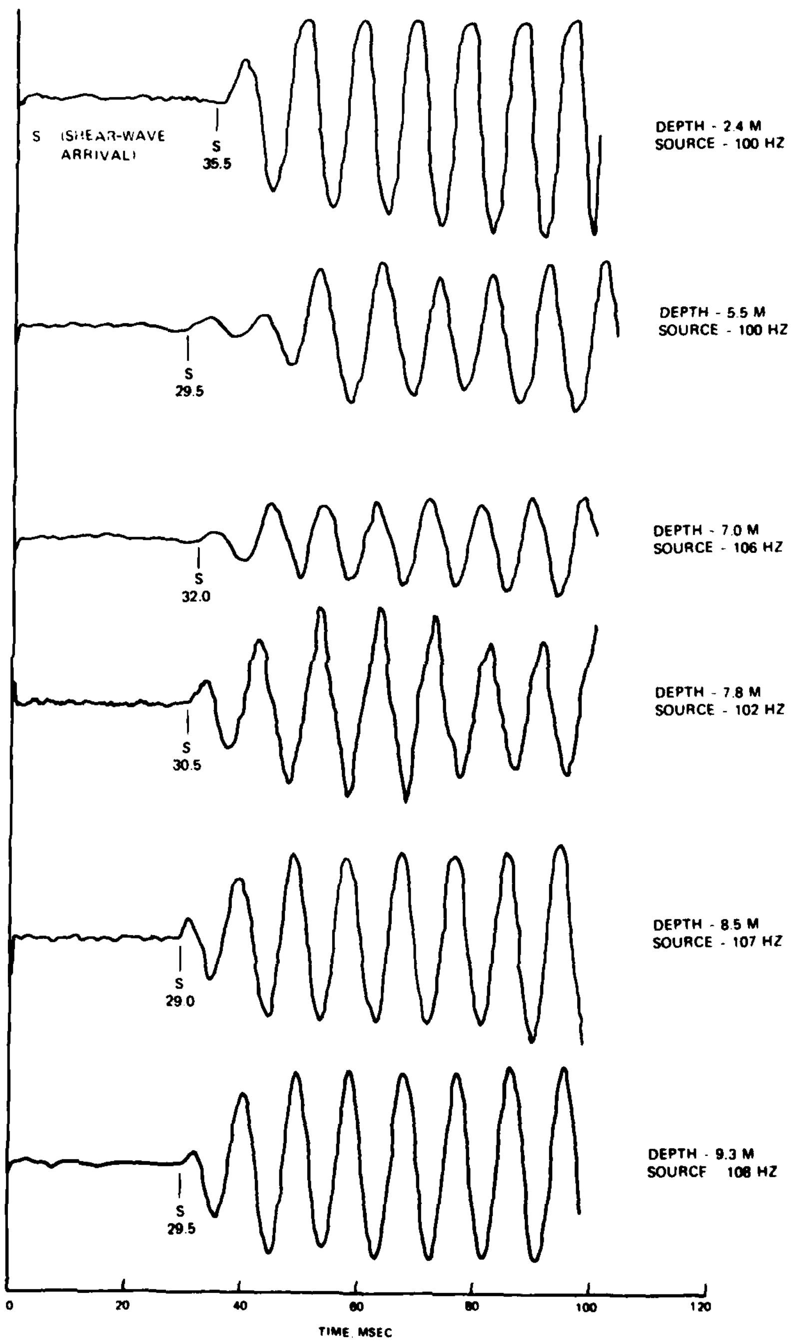


Figure 4.5c. Crosshole seismic test results. Man-made cavity in soil. Source-receiver separation, 6.1 m; depth to center of cavity, 6.7 m; diameter of cavity, 1.2 m

upward to the bedrock surface, a feature which is frequently seen in association with karst cavities, can be expected to produce a travel time anomaly large enough to be detected. For this reason, the method may be more useful in karst than in pseudokarst cavity problems. As in the crosshole test, it is preferable also to examine first-arrival amplitudes for possible diffraction patterns due to cavities, as suggested by Dresen (1973).

Acoustic resonance

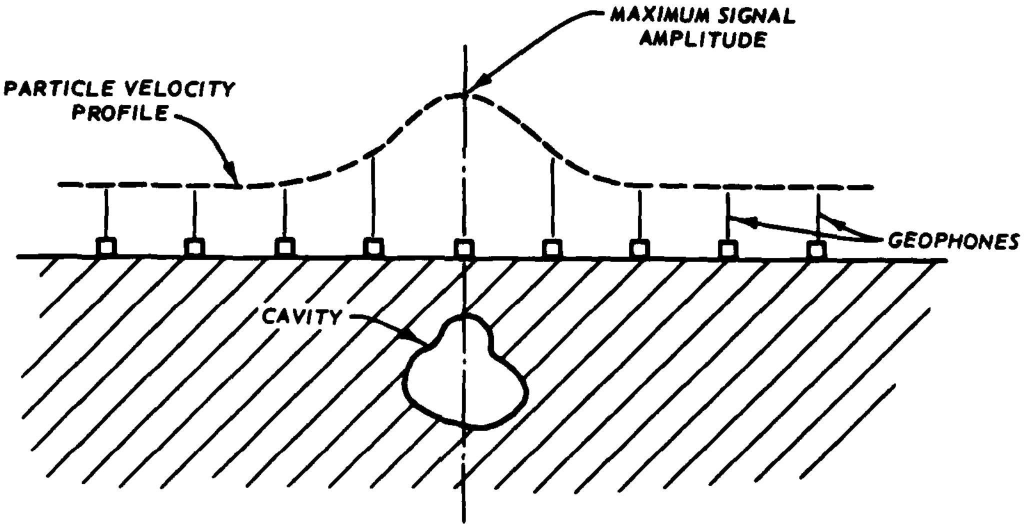
The idea that high amplitude oscillations could be induced in the air or water filling subsurface cavities by an incident seismic signal has long been considered. An apparently convincing demonstration of this acoustic resonance effect was presented by Watkins, et al., (1967) for a survey over a known lava tunnel. Similar results were noted by Godson and Watson (1968) during a survey at a reservoir site experiencing subsurface leakage; however, extensive drilling failed to find cavities. Rechtien, et al., (1976) report several seismic indicators of the presence of cavities, but the resonance effect reported by Watkins, et al., was never observed.

The studies cited above used transient sources. Work reported by Savage (1977) used a vibrator on the ground surface to apply a sinusoidal excitation with slowly swept frequency (0-200 Hz). With this system it is possible to excite resonant modes in cavity systems. Magnitudes of particle motion on the surface are then mapped by means of sensors placed in a grid pattern about the vibrator (in practice, a single sensor moved around the grid). Maxima in the surface particle motion contours have, in some instances, been successfully used to delineate cavity systems. There are, however, several factors that can complicate motion amplitude analysis using surface vibratory souces. Certain stratigraphic configurations may create geometrically fortuitous conditions that cause unusually high amplitudes at some locations, and low amplitudes at others, through interference of refracted or reflected waves. Also, departures from a "normal" amplitude decay curve may be caused by the relationship of the vibrator contact plate dimension to the Rayleigh-wave wavelength (Weiss, 1966).

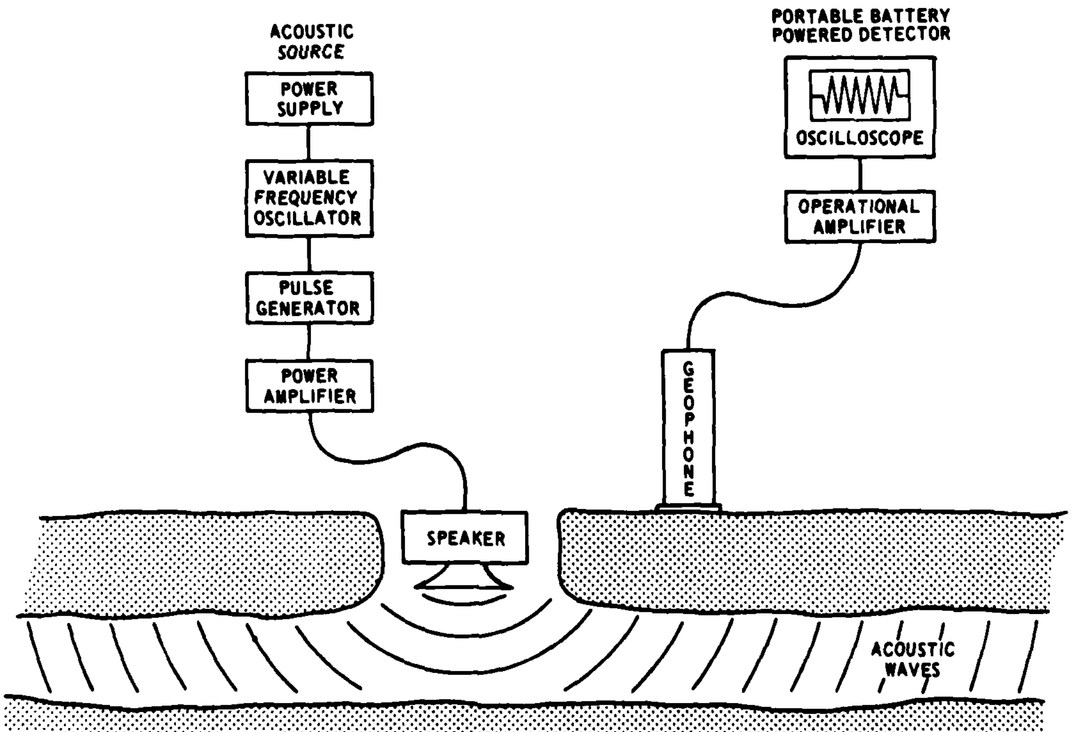
A related method consists of resonating a cavity system by a source placed directly in it, and detecting and delineating the system by surface sensors in the same manner as used by Savage (1977). This technique has been used successfully by Ballard (1977) and Cooper and Bieganousky (1978) to delineate cavity systems, and is further described by Curro, et al. (1980). The basic principle of the technique is illustrated in Figure 4.6, where Figure 4.6a represents a particle velocity profile across the cavity shown in a perpendicular section in Figure 4.6b. A speaker is lowered into either a natural cavity opening or a borehole that intersects the cavity and swept through some frequency range (typically 20-200 Hz) until a resonance condition is detected. Then with the source signal held constant in frequency and amplitude, a grid pattern search with a single, hand-held sensor probe is conducted. A contour map of the peak signal amplitudes at the grid points can be prepared, and the data is easily interpretable in the field. The technique appears to work quite well, at least for relatively shallow, air-filled cavity systems (say to a depth of 15 m, or 50 ft). Recent tests conducted by Cooper (1981) at Manatee Springs, Florida, showed that a sonar source suspended in a water-filled cavity system can be used to produce surface-mappable signals considerably deeper (100+ ft) and farther (250+ ft) than a loudspeaker in an air-filled system.

Electrical Resistivity Methods

Overall, resistivity methods probably represent the most frequently used geophysical methods for site investigations in karst areas or in searches for abandoned mines, and also probably have enjoyed the most general success. The reasons are that (a) the variety of possible electrode arrangements make the methods quite versatile, (b) the methods are easy to apply in the field, (c) many times only a qualitative interpretation suffices, and (d) cavities most commonly represent a very high-contrast anomaly even though sometimes relatively small in size. Commonly used electrode configurations are illustrated in Figure 4.7. The major



a. Hypothetical particle velocity profile across cavity



b. Illustration of acoustic resonance technique using subsurface source

Figure 4.6. Acoustic resonance survey

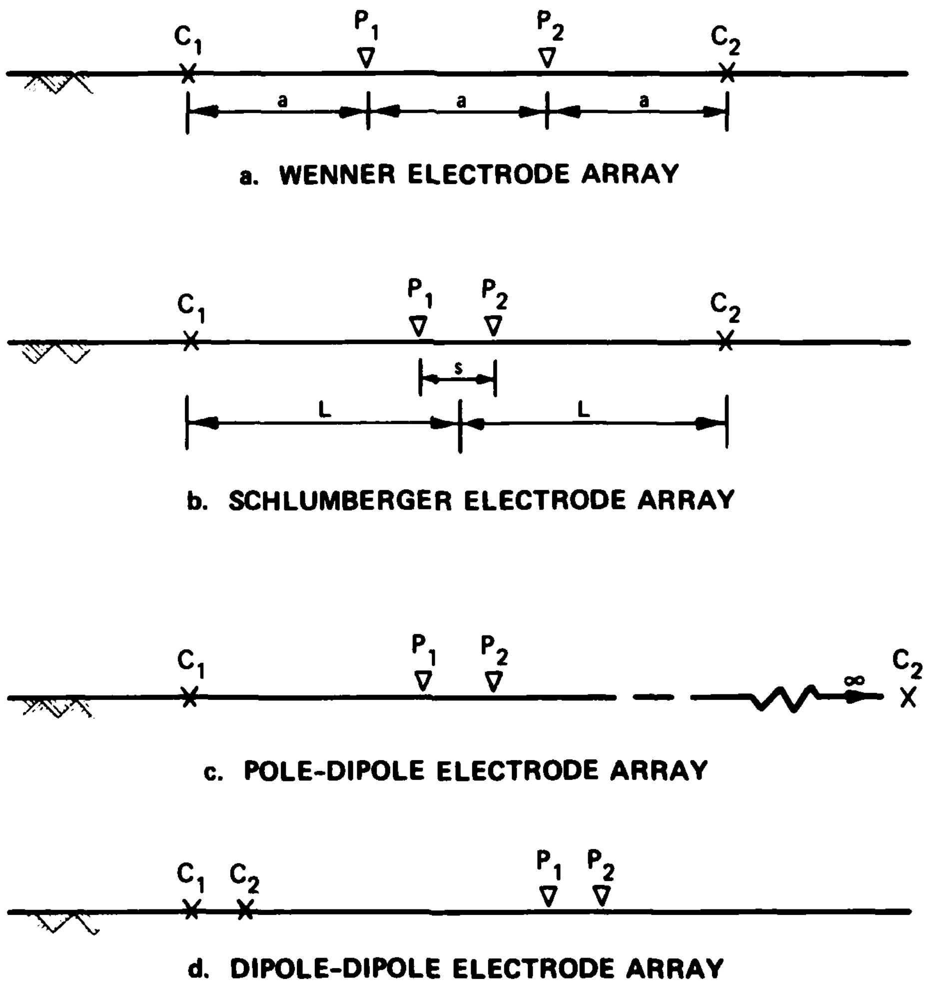


Figure 4.7. Commonly used resistivity electrode arrays

limitation in resistivity methods is that as the depth of investigation increases (i.e., the electrode array length increases) the volume of earth material involved in the measurement increases (as the cube of electrode spacing, other things being equal) to the point where the effect of moderate-sized cavities on readings is small. Thus, the usefulness is limited to shallow depths. Bates (1973) suggests 50 m.

Resistivity sounding

Resistivity sounding to obtain vertical resistivity profiles can, in principle, be accomplished using all of the electrode configurations in Figure 4.7. Most field work, however, is done with the Wenner array (Figure 4.7a) in which all electrodes are moved outward symmetrically from the array center; or the Schlumberger array (Figure 4.7b), in which potential electrodes are fixed while current electrodes are moved outward symmetrically from the array center. In principle, a cavity, if fortuitously located approximately beneath the center of a sounding array, should produce a high or low resistivity anomaly depending on whether it is air-filled, or water- or clay-filled, respectively (Love, 1967; Brooke and Brown, 1975; Fountain, et al., 1975; Palmer, 1954).

Figure 4.8 illustrates the results of a Wenner sounding directly over a known cavity feature (Fountain, et al., 1975), indicating the presence of two air-filled cavities (the depth to the cavities is not equal to the electrode spacing, a, but is related to it). In general, however, in a case such as shown in Figure 4.8, it is difficult to discriminate between cavities and layers of higher resistivity without supplementary geophysical and geological information or multiple soundings in the area around such an anomaly. Soundings conducted for the purpose of cavity detection will require considerably more data points than soundings for the purpose of identifying subsurface stratigraphy. Another problem with resistivity soundings is that lateral near-surface resistivity variations (due to variations in depth to rock and in degree of weathering of near-surface rock), which are common in karst areas, could greatly complicate the interpretation. Another is that the sounding must be done directly over the cavity in order to detect it. Thus, the

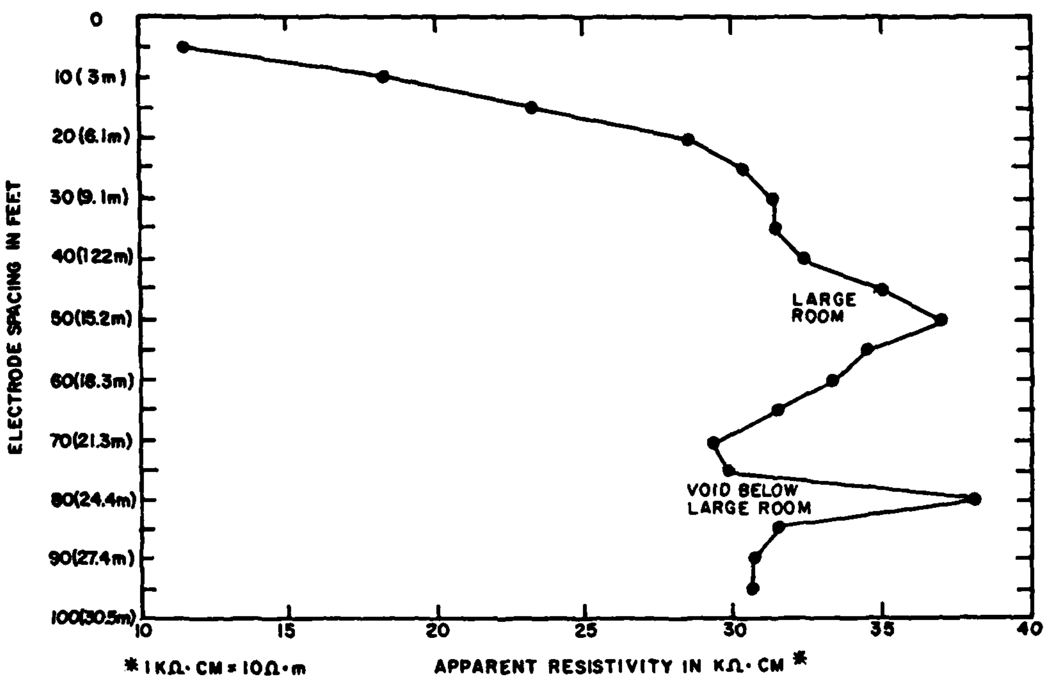


Figure 4.8. Results of resistivity sounding with Wenner array, showing the presence of two air-filled cavities (Fountain, et al, 1975)

resistivity sounding technique is a relatively inefficient method for areal surveys for the purpose of cavity detection.

Resistivity profiling

All of the electrode arrays in Figure 4.7 can be used for resistivity profiling, in which the entire array is moved in increments along a profile line with a fixed electrode spacing. The Wenner array is most frequently used for this type of survey. The result of this procedure is a profile of apparent resistivity for a more or less uniform depth of investigation. If this procedure is repeated for a number of profile lines at a site, the resulting grid of apparent resistivity data points can be contoured. Contour plots preferably should be made for two or more different electrode spacings (i.e., different effective depths of investigation) for a site (Stephens, 1973). Resistivity profiling has been used effectively for numerous site investigations in karst regions and in searches for abandoned mines (e.g., Love, 1967; Burton and Maton, 1975; Curro and Butler, 1980; Millet and Moorhouse, 1973; Cooper and Bieganousky, 1978; McDowell, 1975; Dearman, et al., 1977; Stephens, 1973). The principal concern in the use of the method for cavity detection is to choose judiciously the proper electrode spacings to allow discrimination between near-surface effects on the data and effects due to cavities. While the profiling method can give some indication of anomaly depth and size, the primary use is to survey rapidly an area to locate anomalies; determination of depth and size can be done more reliably by other geophysical methods and by drilling.

Pole-dipole surveying

A method of resistivity surveying using the pole-dipole array (see Figure 4.7c), developed by Bristow(1966) and modified by Bates (1973), appears to be well suited for the detection of localized anomalies such as cavities. The current electrode C_2 is placed as far away from the survey area as practicable. The potential electrode pair is moved outward on both sides of the current electrode C_1, keeping the spacing $P_1 P_2$ constant (typically 2-3 m) to a distance from C_1 somewhat greater than the desired depth of investigation (typically 50 m or less). Overlapping lines are used for multiple coverage. The graphical interpretation procedure, described by Bates (1973) and Fountain (1975) tends to account for the normal variation of resistivity with depth and selects high or low resistivity anomalies with respect to the normal variation. Figure 4.9, from Bates (1973), illustrates the graphical procedure for location of anomalies. Circular arcs are drawn through locations of potential electrodes showing anomalous potential differences, with the C_1 position as center. Intersections of the arcs are assumed to define the locations of anomalies. Figure 4.9 shows two anomalies located by three traverses with different C_1 locations. The interpretation procedure and the multiplicity and overlapping of data tend to eliminate spurious anomalies and allow discrimination between near-surface anomalies and anomalies at depth. This technique has been used successfully for a number of investigations in karst regions (Bates, 1973; Curro

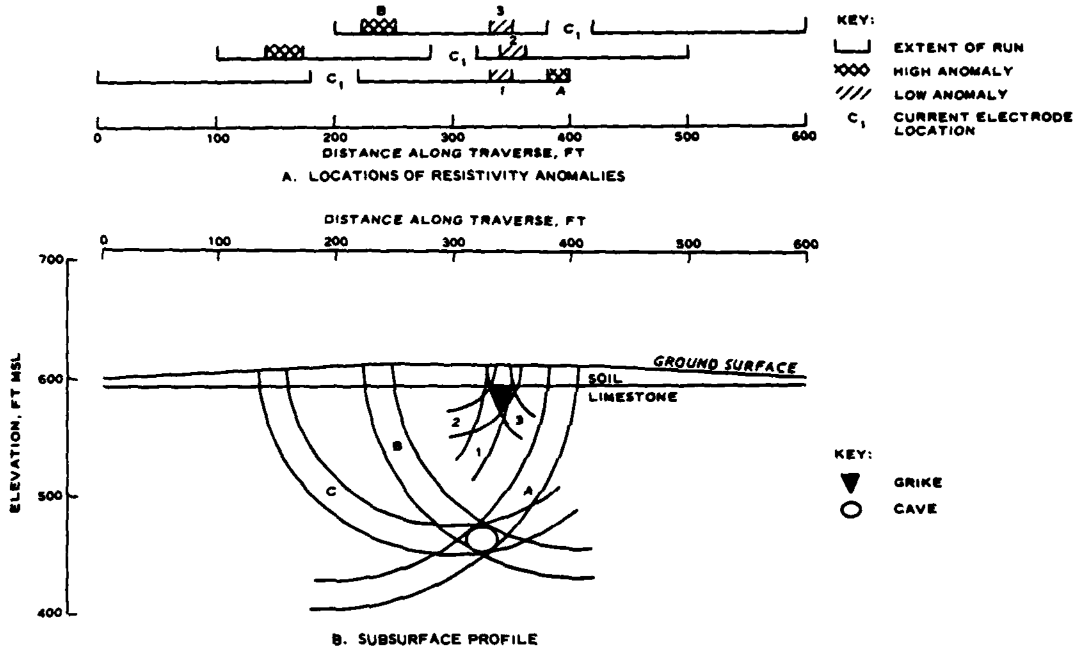


Figure 4.9. Simplified example of graphical interpretation of pole-dipole resistivity data for anomaly location (Bates, 1973)

and Butler, 1980; Cooper and Bieganousky, 1978; Fountain, et al., 1975) and also for mine location in hard rock (Fountain, 1975). These investigations offer strong empirical support for the Bristow-Bates graphical method, in spite of the objection that it does not have a rigorous theoretical basis. The model on which it is based is qualitative and to some extent self-contradictory. It should therefore be used with due recognition of its theoretical limitations. An additional drawback has been the time required to conduct the field tests and interpret the data. However, an automated system for pole-dipole surveys developed by the Southwest Research Institute (SWRI), San Antonio, Texas, eliminates the theoretical objection and promises to make the technique more efficient (Spiegel, et al, 1980).

Subsurface methods

The surface resistivity methods discussed have borehole counterparts, but borehole resistivity surveys for the specific purpose of detecting cavities have not been numerous (Fountain, 1975). A crosshole resistivity technique which has been used by the Waterways Experiment Station, Vicksburg, Mississippi, shows promise but still needs further verification (Butler and Murphy, 1980).

Microgravimetric Methods

Gravimetric techniques for detection of cavities associated with karst conditions and abandoned mines have been used extensively in Europe at least since the early 1960's (Neumann, 1977; Omnes, 1976). The availability of a true microgravity meter in the late 1960's and a better appreciation of the exacting requirements on the quality of the survey gave impetus to the use of gravimetry for cavity detection and geotechnical applications in general.* References discussing successful applications of microgravimetry to geotechnical problems, particularly subsurface cavities, are numerous (e.g., Curro and Butler, 1980; Butler, 1979, 1980; Palmer, 1954; Omnes, 1976; Arzi, 1975; Colley, 1963; Neumann, 1967, 1973, 1977; LaFehr, 1979; Lakshmanan, et al., 1977; Lakshmanan, 1973; Mongelli and Ruini, 1977). Essentially the technique consists of relative measurements of the force of gravity along a profile line, or more often, on a grid pattern (typically 3-10 m grid spacing). After a series of corrections and adjustments to the data, a contour map of gravity anomalies caused by density variations in the subsurface is produced. Figure 4.10a is an example of a gravity contour map over a known subsurface cavity system, Medford Cave, in central Florida (Curro and Butler, 1980; Butler, 1979). The closed contours in the center of

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* The use of a gravimeter with microgal sensitivity, such as the LaCoste and Romberg Model-D, is considered essential for general success of microgravimetric techniques.

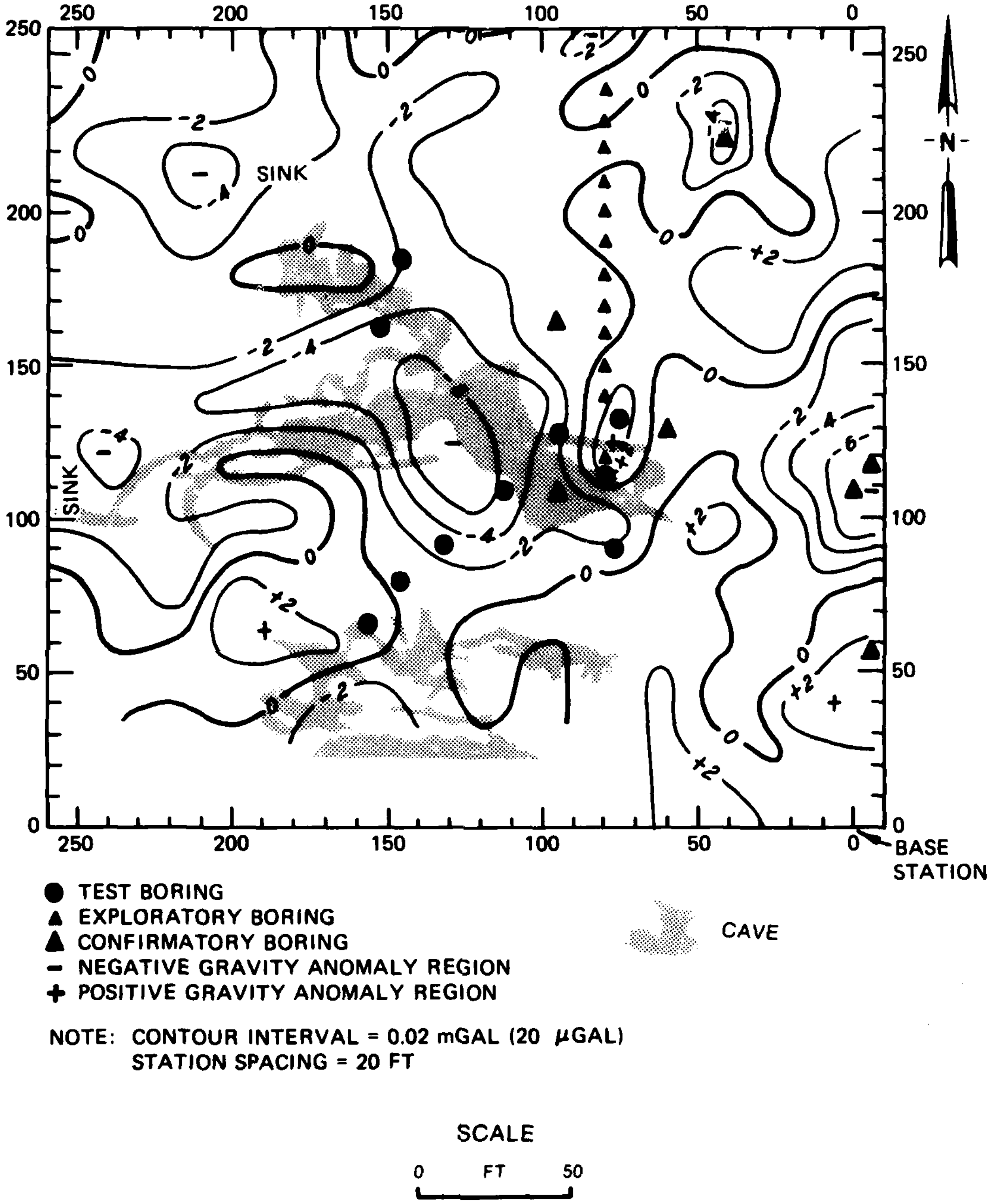

Figure 4.10a. Residual gravity anomaly map from microgravity survey at cavity test site.

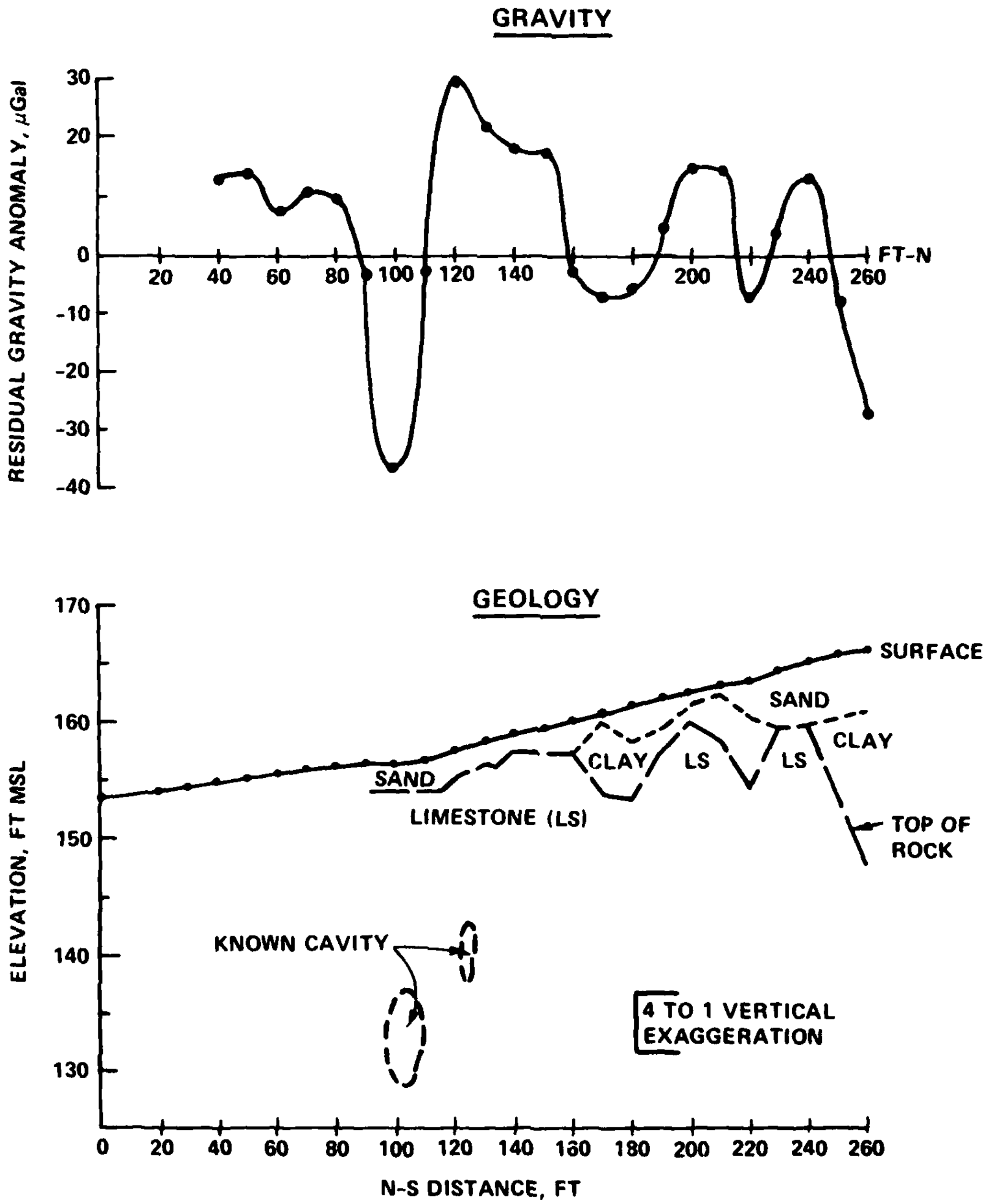

Figure 4.10b. N-S gravity and geology profiles along the 80-ft line of Figure 4.10a.

the map represent a negative anomaly of about -70 microgral* which satisfactorily matches the known cavity system in the area. Other negative anomalies on the map were found by drilling to be air- or clay-filled cavities or clay-filled grikes or pockets in the surface of the limestone. Figure 4.10b shows gravity and geologic profiles along the N-S line 80 ft west of the base station in Figure 4.10a; note the close correlation between the gravity values and the known geologic conditions.

The microgravity survey itself requires only one experienced operator, although a two-man crew could proceed more efficiently. A relative elevation survey of the site is required at survey grid points. Depending on grid point spacing and logistics, from 50 to 80 gravity readings can be obtained in a work day. The microgravity survey shown in Figure 4.10 required 7 man days, and establishing the site grid and determining relative elevations required 6 man days (3 days for two-man survey party).

An extension to the microgravimetric technique involves the determination of the vertical gradient of gravity using a portable tower structure and the horizontal gradient of gravity using closely spaced (3-10 m) surface stations (Butler, 1979). Fajklewicz (1976) reports considerable success with this technique in detecting abandoned mine shafts and adits. However, it must still be considered to be in the development stage. Borehole gravimetry uses gravity gradients measured in a borehole to produce a vertical profile of average in situ bulk density (Snyder, 1976). This method has been used successfully to detect zones of low average density related to high porosity, and thus has application to investigations in karst regions. A survey from a single borehole is capable only of defining the depth of a zone of anomalously low density, but the location and areal extent of the anomaly could be defined by additional surveys in other locations.

Of all the geophysical methods, microgravimetry comes closest to allowing a positive statement regarding the presence or absence of subsurface cavities at a site. For any particular microgravimetric

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* 1 microgral (μgal) = 10^{-6} cm/s^2

anomaly, it is not possible in general to identify a unique source, although knowledge of the geology may considerably restrict the possibilities. The same is true of any geophysical method; drilling or direct access is the only positive method for identification of the subsurface conditions causing geophysical anomalies. However, in gravimetry, the absence of anomalies in a site survey has considerable significance. For any hypothesized cavity (filled or unfilled) that might be considered to pose a threat to foundation bearing capacity in subsequent site use (see Chapter V), it is always possible to calculate the minimum depth at which the cavity can exist without being detected. Even considering reasonable experimental errors in the data, such calculations are generally conservative, since experience shows that gravity anomalies due to cavities in karst regions are greater (generally by a factor of two or more) than those calculated on the basis of cavity dimensions (Omnes, 1976; Neumann, 1973), due to increased porosity (decreased density) caused by fracture and solution in the rock around the cavity. Although it is possible for gravity anomalies due to cavities at depth to be masked by shallower anomalous conditions, such as pinnacles at the top of the limestone, anomalies that could be masked by pinnacles are likely to be too small to pose a threat to foundation stability (Butler, 1980).

Electromagnetic (EM) Methods

Of the various EM methods that have been used for cavity detection studies, only two will be discussed in this section: (a) the so-called surface ground-probing radar* methods; and (b) borehole radar methods. Some other methods are described in recent papers by Gabillard, et al., (1977), Gabillard and Dubus (1977) and Dupis (1977) who discuss the

* The term radar is used because of its common use in the literature to describe the EM methods discussed here. Most of the systems in use operate in the VHF band (30 to 300 MHz).

application of surface loop and line antennae and an artificial magnetotelluric method to the cavity detection problem. While these methods look promising, application of these and similar techniques to shallow cavity detection is still experimental in nature.

Surface ground-probing radar

The results of considerable research and practical application of surface ground-probing radar methods to site investigations have been published since 1970 (e.g., Butler and Murphy, 1980; Curro and Butler, 1980; Fountain, et al., 1975; Rubin and Fowler, 1978; Moffat and Puskar, 1976; Rosetta, 1977; Morey, 1974). In general, the most practical of these methods use surface transmitter and receiver antennae mounted a short distance apart on a sled which can be pulled by hand or towed behind a vehicle along a surface traverse. The procedure can properly be referred to as vertical EM reflection profiling. Output can be in the form of a time-section, i.e., a graphic record of two-way reflection time versus distance along the traverse line. As in seismic reflection, if the wave propagation velocity is known as a function of depth, the time-section can be converted to a depth-section. Under favorable conditions, the graphic record reveals to an experienced interpreter the presence and continuity of subsurface reflecting horizons as well as the presence of localized subsurface reflectors such as cavities. In general, the method is both time- and cost-effective and is capable of high resolution of subsurface features.

The most serious drawback of the surface ground-probing radars is their extremely site-specific performance. A surface radar system may work well on one site and fail completely on another, with no well-understood or consistent explanation. Where the method is successful, however, data of very high resolution can be obtained, and the cost is moderate. Two factors have been observed to lead consistently to poor radar performance in attempts to detect cavities below top of rock: (a) the presence of thick soil cover, particularly when the soil has a high water content; and (b) the presence of significant amounts of clay in the soil, regardless of thickness. In certain ideal situations, depths of investigation of 30 m or more can be expected in radar surveys (Cook, 1975); however, in general, radar should be viewed as a tool for relatively shallow depths of investigation (to about 10 m; Butler and Murphy, 1980). The most favorable conditions for radar surveys would be found where the soil cover has been removed and the water table is relatively deep. In the selection or design of a radar system, there is a tradeoff between the desirability of high-frequency systems, for resolution of small, localized subsurface features, and the need to use lower-frequency systems to increase depth of penetration.* It seems that an optimum frequency may be about 100 MHz (center frequency for pulsed systems). Of course, great depths of penetration can be achieved by increasing transmitter output power, although there is a practical limit to this approach. Clearly, more documented case histories of surface radar applications to site investigations are needed in order to better define the site-specific limitations of the technique.

Borehole EM methods

The use of borehole radar antennae in either a reflection mode (single borehole survey) or a transmission mode (crosshole survey) avoids the problems of having to penetrate the soil cover, which limits the surface radar methods. Extremely promising results have emerged from cavity detection studies using borehole radar systems (Curro and Butler, 1980; Davis, et al., 1977; Lytle, et al., 1976, 1977; Kaspar and Pecen, 1975). Figure 4.11 shows two crosshole radar records obtained by the Southwest Research Institute (SWRI) at a test site in Florida (Curro and Butler, 1980). The first record was obtained in a survey between two boreholes with no known cavities between them; the second, between two boreholes straddling a known cavity (Figure 4.12). The cavity is indicated by a 20 ns travel time, as compared to 40 ns in the unaffected parts of the record. The two tests shown in Figure 4.11 required about 5 minutes each to conduct.

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* Attenuation of EM waves is frequency-dependent, and the rate of attenuation generally increases with frequency.

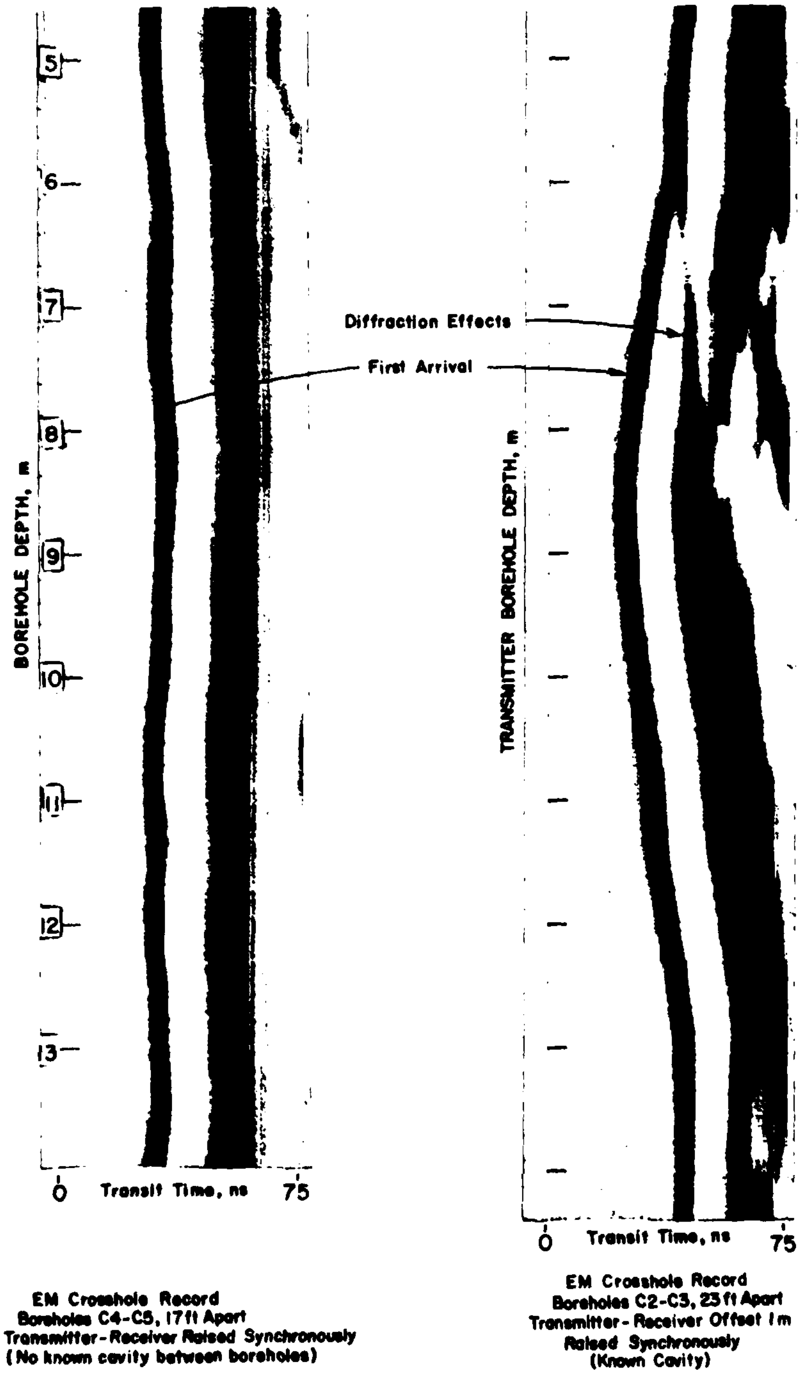


Figure 4.11. Typical crosshole EM (radar) records with pulsed EM system at cavity test site

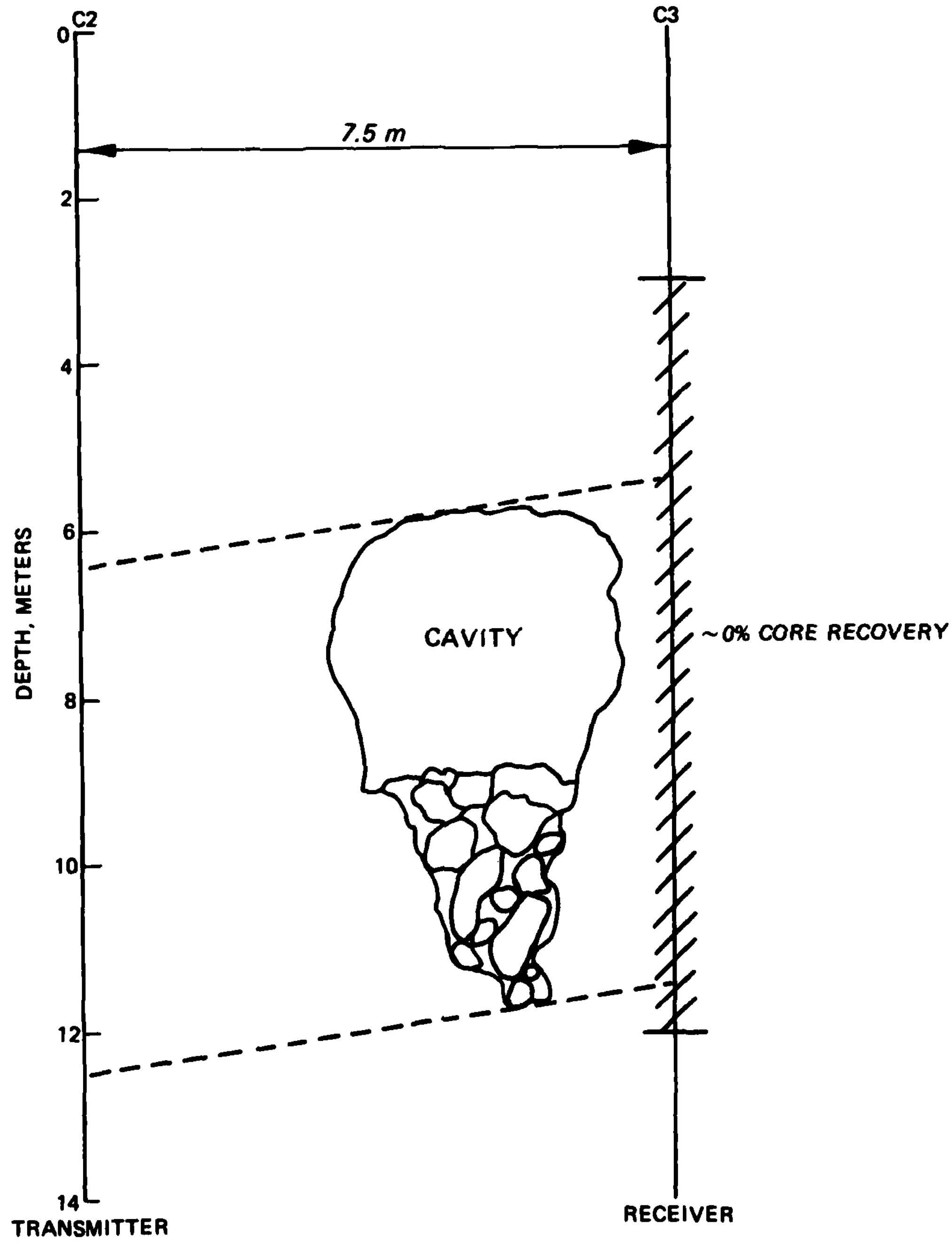


Figure 4.12. Crosshole EM (radar) test geometry for record in Figure 4.11.b. Transmitter offset 1 m downward from receiver, transmitter and receiver raised synchronously

RECONNAISSANCE SURVEYS FOR CAVITY DETECTION

Methodology

For reconnaissance geophysical site surveys in areas of possible cavities, the objective is the location in plan of anomalous regions or zones. It is not necessarily expected in this type of survey to determine depths, sizes, or geometry of the cavities. This type of s... program is appropriate in the preliminary or site selection phase in the early stages of the site-specific investigations in order to guide the planning of the initial drilling and sampling program and aid in the placement of critical structures on the site. In both applications, the objective is the rapid assessment of site conditions over a relatively large area in a cost-effective manner, and absolute accuracy is not needed.

Generally, site geophysical surveys are in a grid pattern or on a set of parallel profile lines relative to a site reference grid. Exceptions to this procedure might occur when selected geophysical survey lines are arranged to be perpendicular to a mapped linear geologic feature, such as a fault or fracture trace, a line of sinks or surface depressions, or an airphoto lineament. Three considerations typically will determine the geophysical survey grid or profile spacing: (a) the required or desired resolution; (b) the known or estimated average depth to top of the suspected cavities; and (c) the required or desired depth of investigation. In some cases the input guidance for planning the geophysical survey, particularly for items (a) and (c) may be nothing more than that it is desired to detect anomalies as small as possible and as deep as possible; the decisions thus may reduce to what can be done within established time and cost limits. If specific guidelines are given, such as maximum tolerable cavity size at a given depth, as determined by the design of structures and foundations, and the minimum required depth of investigation, the design of the geophysical surveys can be optimized. In general, it is meaningless and sometimes counterproductive to try to define size/depth resolution limits for each geophysical method since there are so many exceptions to any rule. In the detection of individual solution features, most of the methods are probably capable of detecting a feature with a characteristic cross-section diameter of 1 m at a depth of 10 m. For some of the high-resolution methods, this limit can be extended to a diameter of 0.5 m at the same depth.

Geophysical Reconnaissance Programs

The geophysical reconnaissance survey program should be planned on the basis of the use of complementary methods, since no single geophysical method should be relied on to assess subsurface conditions at a site. Complementary methods are defined as those which sample different geophysical parameters; thus, neither two different types of resistivity surveys nor two different types of seismic surveys would be considered complementary geophysical surveys. Table 4-1 presents candidate geophysical methods for reconnaissance site surveys for cavity detection, with the methods grouped in "most promising" and "borderline" categories. No preferred ranking is implied by the order in which the methods are listed. Methods listed in the "borderline" category are considered to meet at least one of the following criteria: (a) the method is useful in certain specific situations; (b) advances in the state of the art in the near future may make the method more useful; or (c) the method is useful but may be too time consuming to be time- or cost-effective. A geophysical reconnaissance program should consist of at least two of the methods in Table 4-1, preferably including at least one from the "most promising" category.

One example of a versatile and reliable reconnaissance program would consist of a microgravity survey and a resistivity survey using the Wenner array on a grid pattern. For a reconnaissance microgravity survey, a station grid spacing of 5 to 10 m is appropriate (using the smallest possible spacing consistent with time and money constraints). A north-south and east-west survey grid is convenient though not

TABLE 4-1. CANDIDATE GEOPHYSICAL METHODS FOR CAVITY DETECTION PROGRAM (RECONNAISSANCE SURVEYS)

Most Promising

Surface Electrical Resistivity Profiling (Grid Contouring)

Microgravimetry

Constant Spacing Seismic Refraction

Seismic Fan Shooting

Borderline

Standard Surface Seismic Refraction

Pole-Dipole Electrical Resistivity Surveying (Bristow-Bates)

Surface Ground-Probing EM (Radar)

necessary. It is not difficult to keep possible errors due to gravity data corrections in the μgal range by surveying relative elevations to ± 0.3 cm (0.01 ft) or better, by determining relative north-south station locations to better than 1 m, by determining or estimating near-surface soil and rock densities to ± 0.1 g/cm^3, and by reoccupying the base station at least once per hour. With careful measurements, including about a 20 percent station reoccupation rate, gravity anomalies of 10 μgal should be detectable.

While it is not possible to specify a single resolution limit and depth of investigation for a microgravity survey, due to the dependence of anomaly magnitude on the size, depth and density contrast of the causative structure, it is possible to make some strong positive statements about cavities that can and cannot be present. Figure 4.13, for example, presents the maximum gravity anomaly for a horizontal, cylindrical cavity with density contrast $\Delta\rho = -1.0$ g/cm^3 (possibly representative of a clay-filled cavity in limestone) as a function of

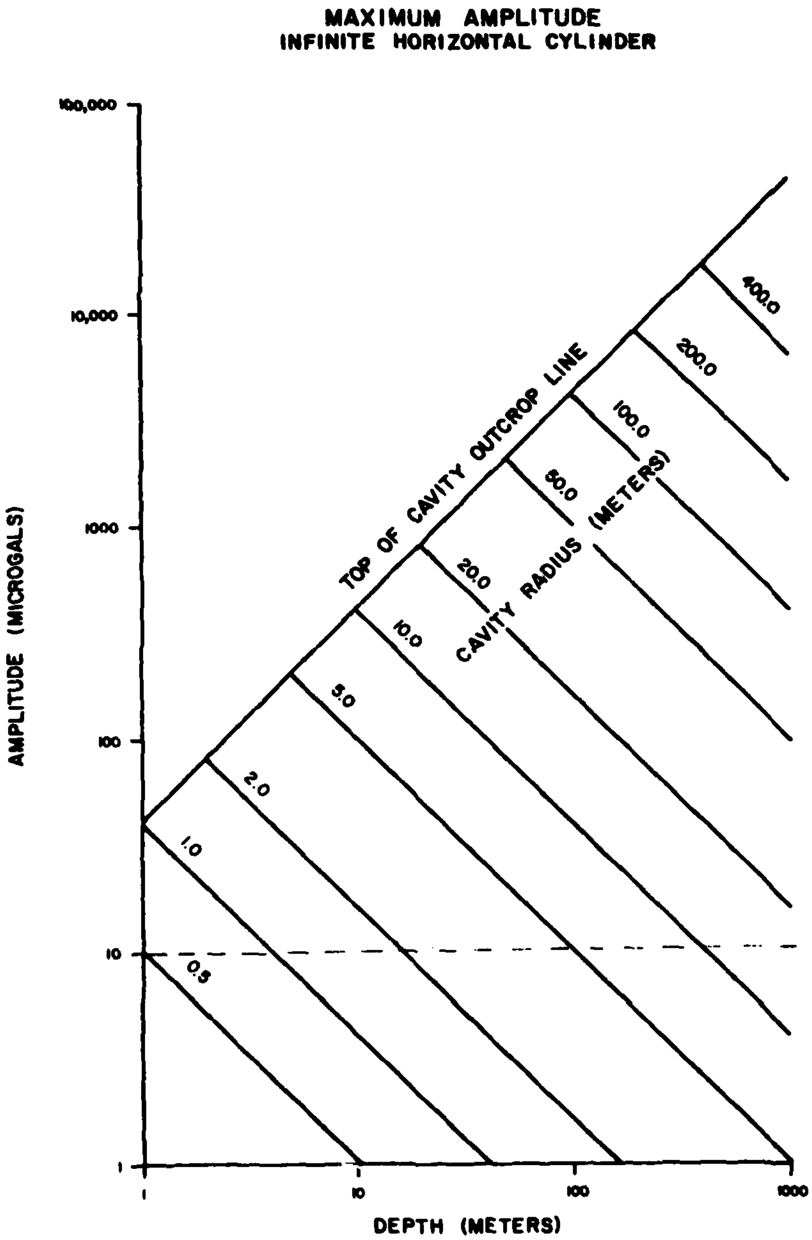


Figure 4.13. Maximum gravity anomaly above a long, horizontal, cylindrical cavity with density contrast $\Delta\rho = -1.0\ g/cm^3$ (LaFehr, 1979)

depth to cavity center and cavity radius (La Fehr, 1979). The horizontal cylinder represents a reasonably good model for many field situations. The dashed horizontal line at 10 μgal defines the conditions under which a cavity should be detectable (i.e., all cavities whose radii and depths plot above the line should be detectable) by microgravity surveys. Actually, this figure is conservative, because a water-filled cavity in limestone would likely represent a density contrast of -1.5 g/gm^3, while an air-filled cavity would likely represent a density contrast of -2.5 g/cm^3; and gravity anomalies due to solution cavities are, in general, larger by a factor of two or more than that calculated based on idealized geometry. Similar figures can easily be produced for any density contrast and any cavity geometry.

Wenner resistivity profiling surveys, complementary to the microgravity survey, should be conducted in a grid pattern with 5-10m station spacing. At least two electrode spacings (see Figure 4.7a) are desirable. A survey with a short electrode spacing should be conducted to map variations in overburden thickness and properties, with the spacing selected to be slightly greater than the mean estimated or determined overburden thickness. The survey with longer electrode spacing would then be conducted to detect cavities, with the spacing selected to be somewhat greater than the desired depth of investigation (for example, if the desired depth of investigation is 20 m, the spacing might be 25 m). If the suspect zone is not the first layer under the overburden, an additional survey with intermediate spacing is recommended specifically to map variations in the intervening rock formations.

The resistivity profiling surveys proceed quite fast and require very little data processing other than preparation of contour maps. Thus, interpretation of results can be available shortly after completion of the survey, and preliminary assessments of results are easily made during the survey. Microgravimetry is a somewhat slower method both in data acquisition and data processing; however, it is imperative that data be processed in a preliminary fashion in the field to insure data quality, and hence, indications of major anomalies will be available in the field.

As discussed earlier, the surface ground-profiling EM (radar) methods are capable of very high resolution and high rates of areal coverage in the field. For reconnaissance surveys, profile lines spaced about 8-10 m apart are recommended. The site-specific limitations of the radar method were discussed earlier and must be emphasized. However, if conditions at a site are favorable, the radar method deserves serious consideration. The method is rapid enough that it could be used for verification of anomalies detected by other geophysical methods even in the reconnaissance phase.

The other geophysical methods listed as "borderline" in Table 4-1 can be of great use for some sites. The surface seismic refraction method is a common and well-understood geophysical method, and should be considered for reconnaissance programs if site conditions appear favorable. Seismic refraction should not be relied on as a principal cavity detection method, but it is very useful in elucidating other aspects of soil and rock conditions. Pole-dipole resistivity surveying may prove to be a valuable reconnaissance technique when automated field procedures and data processing methods are commonly available.

Presentation of Data

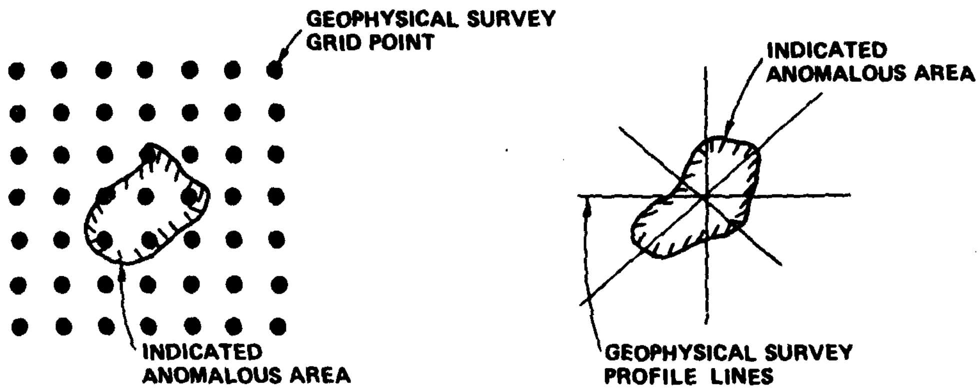
The most readily useful forms of data presentation from a reconnaissance survey program are contour maps or other plan maps denoting anomalous areas. In particular, the presentation should emphasize correlations of the geophysical data with other information such as borehole data, surface features such as sinks, and the like. An attempt should be made to assess data accuracy, anomaly resolution limits, depths of investigation, and at least qualitatively, the possibility that a cavity of size sufficient to pose a threat to subsequent site use could be present but undetected. At an early stage, a sufficient number of anomalies should be selected for verification drilling to permit an assessment of the reliability of the geophysical results. Based on the results of the verification drilling and the geophysical reconnaissance surveys, a preliminary assessment can be made of the extent of solution effects or the probable sizes and locations of cavities. In addition, boring locations for anomaly verification may be specified and input can be provided on possible cavity size and orientation for the determination of orientation of a systematic drilling and sampling grid.

HIGH-RESOLUTION SURVEYS FOR CAVITY DELINEATION

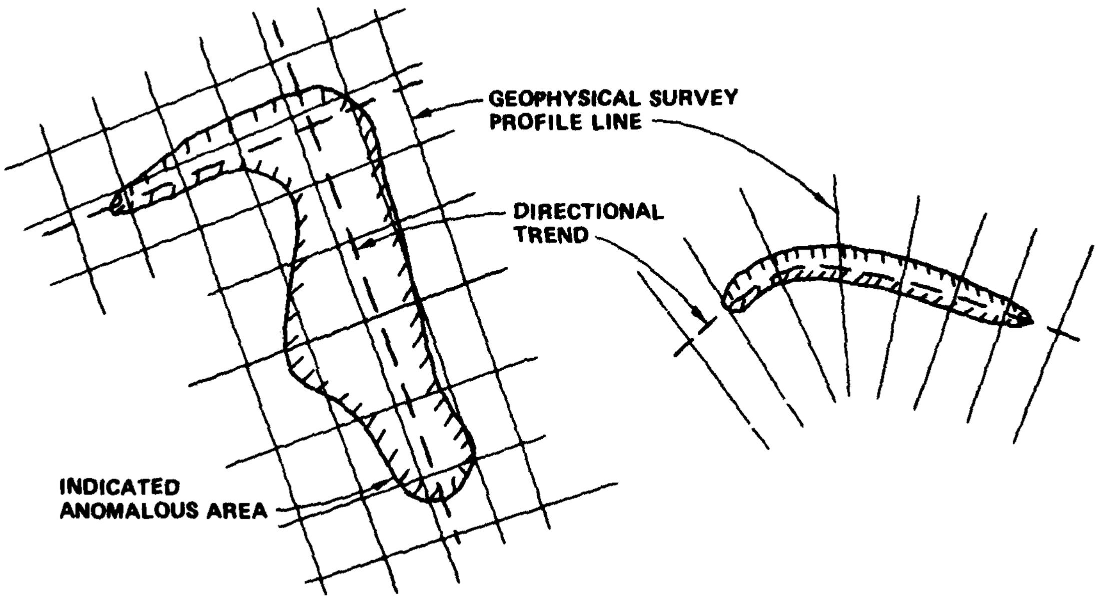
Methodology

Anomaly delineation implies the use of high-resolution geophysical surveys or drilling of high areal density to map in detail anomalous areas detected by reconnaissance geology, geophysics, and/or drilling. Objectives of delineation surveys include: determination of geometry (including dimensions); determination of depths; detecting connections between anomalous areas; estimation of volumes of cavity systems, for planning of remedial work; and determination of the nature of any cavity-fill material. The cost of adequately delineating complex cavity systems solely by high density drilling is prohibitive in most cases. Thus, a coordinated drilling and geophysical program may be indicated. With systematic drilling at a site either on a grid pattern or on selected profiles, the use of high-resolution crosshole geophysical surveys can significantly increase the minimum necessary borehole spacing, thus reducing cost. In addition, the relatively small foundation areas of critical structures at a site may warrant high-resolution geophysical surveys even if no anomalies were detected in reconnaissance surveys.

High-resolution geophysical surveys for anomaly delineation will involve survey plans or layouts tailored to the indicated anomaly. If the anomaly is isolated, the survey could be a closely spaced grid pattern or selected profile lines crossing the anomaly in several directions, as illustrated in Figure 4.14a. For elongated anomalies with one or more directional trends, profile lines should be oriented approximately perpendicular to the indicated trends, as illustrated in Figure 4.14b. The objective is to define the extent, size, and depth of the anomalous structure. Since one of the objectives of reconnaissance surveys is the recommendation of borehole locations in anomalous areas, high-resolution geophysical surveys can be planned to optimize the benefits of correlation with the borehole data. Also, the use of high-resolution



a. HIGH-RESOLUTION GEOPHYSICAL SURVEYING OF ISOLATED ANOMALOUS AREAS



b. HIGH-RESOLUTION GEOPHYSICAL SURVEYING OF ANOMALOUS AREAS WITH DIRECTIONAL ELONGATION

Figure 4.14. High-resolution survey plans tailored to indicated anomalies

crosshole techniques will require the placement of boreholes in anomalous areas, and every attempt should be made to achieve multiple objectives in the placement and use of the holes.

High-Resolution Survey Programs

Crosshole surveys in a systematic drilling program

Systematic drilling at a site has the purposes not only of detecting anomalous zones but of obtaining samples for laboratory testing and for stratigraphic mapping of the site. The use of standard borehole geophysical logging can significantly reduce the amount of coring that must be performed at a site (Hopkins, 1977). Borehole logs can be run in holes drilled by the most expeditious method and will still allow stratigraphic correlation between holes (i.e., the interval between cored boreholes can be significantly increased). They also are useful in detecting zones of solution activity or high porosity, but not for the detection and delineation of specific cavities that may occur between boreholes. High-resolution crosshole geophysical methods can help to fill the gap.

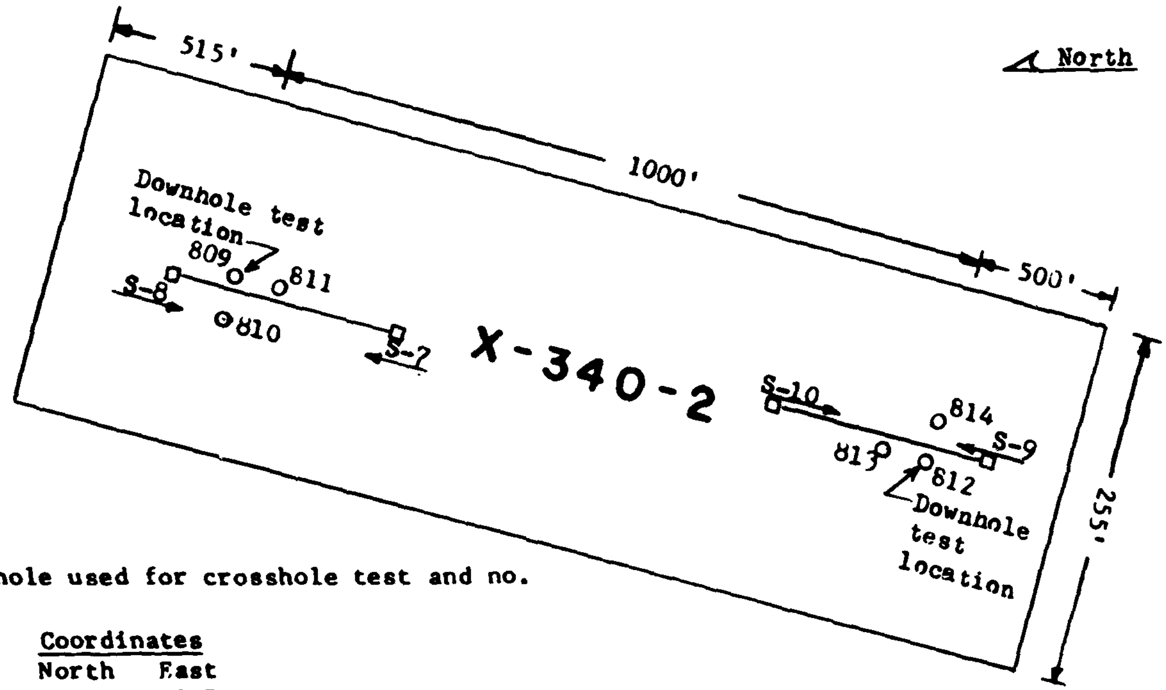
Crosshole seismic methods can be effectively applied in boreholes separated by as much as 15 m. The size of the smallest cavity that can be detected and delineated will obviously increase as the borehole separation increases, and the optimal borehole separation is usually in the range of 6 to 10 m. Both compression (P) and shear (S) wave arrival times and amplitudes should be determined. For the initial survey between a borehole pair, the opposed source-receiver configuration, in which both source and receiver are synchronously raised in their respective boreholes, is preferred, with an in-hole measurement interval no greater than 1 to 2 m. Although both P- and S-wave arrivals can be picked from a single record obtained with an impulsive (or explosive) source, it is preferable to use a vertically polarized S-wave vibratory source, using the highest possible frequency that will allow detection, for the determination of S-wave arrivals. If anomalous arrival times or amplitudes are encountered in the opposed source-receiver configuration survey, offset surveys, which consist of displacing the receiver up or down relative to the source and then synchronously raising the source-receiver pair, should be conducted. Two offset surveys, say with offsets of 1 and 2 m, should be sufficient. The offset surveys achieve three important results: they (a) discriminate between the possibilities of a cavity and a layer of anomalous velocity; (b) give some information about the geometry of cavities; and (c) allow location of the cavities laterally between the boreholes (Curro and Butler, 1980; Dresen, 1973).

Crosshole EM (radar) methods can be applied in a similar manner; however, with EM methods the time required for one survey of a borehole pair is much less, and the vertical sampling interval can be made almost as small as desired. The decreased survey time and sample interval allow increased resolution and larger numbers of offset surveys to be conducted. Resolution is also aided by the short wavelengths of the EM signals.

An alternative to the use of crosshole methods is to conduct a high-resolution pole-dipole resistivity survey, as described earlier, along the line. The potential electrode spacing should be 1.5 to 2 m and the current electrode station spacings should be about 10 m. If the potential electrodes are moved out to say 25 to 30 m on each side of each current electrode station, excellent detection and resolution of anomalies to a depth of 20 to 25 m may be achieved under favorable conditions.

High-resolution surveys for foundations of structures

For foundations of critical structures, a common geophysical objective is the determination of dynamic soil/rock properties for use in dynamic analyses of the foundation. This objective requires the use of seismic methods. Figure 4.15 illustrates a field layout for determination of compression- and shear-wave velocities beneath a large building foundation, and represents typical procedure for this purpose (Curro and Marcuson, 1978). High-resolution crosshole seismic surveys



Legend:

o Borehole used for crosshole test and no.

Borehole	Coordinates North	Coordinates East
809	6134	10172
810	6139	10153
811	6115	10167
812	5168	9914
813	5187	9919
814	5163	9933

□ Shotpoint

S-8 → Surface refraction seismic traverse no. and direction

Figure 4.15. In situ seismic test program for determination of elastic moduli at proposed building site

can thus be used for cavity detection and delineation and serve a dual function, although a denser coverage would be required for cavity delineation than for determination of dynamic properties in the foundation area.

If crosshole seismic surveys are used, an areal coverage technique such as microgravimetry is suitable as a complementary method. The general survey procedure is similar to that for reconnaissance geophysical surveys, except that, for this application, gravity station spacings should be in the 3- to 6-m range. In addition to delineating any cavity systems or fractured bedrock zones present, the results of the microgravity survey can be used to estimate the quantity of grout required to fill the cavity system. Also, if a microgravity survey is conducted after remedial grouting, assessment of effectiveness of the grouting program can be made (Arzi, 1975).

When cavity systems are detected in foundation areas of critical structures, either by drilling or geophysical methods, consideration should be given to drilling a large diameter borehole into the cavity to permit an acoustic resonance survey, using a subsurface source. This survey proceeds quite rapidly and in many situations will identify the extent and directional trends of the cavity system.

Anomaly delineation surveys

For the geophysical delineation of a previously detected anomalous zone at a site, the necessity of conducting complementary geophysical surveys is largely obviated. In principle, any of the "most promising" methods of Table 4-2, if properly applied, could satisfactorily delineate anomalies. The survey grid or profile lines should extend well beyond the indicated anomalous zone in order to define the boundary and detect possible extensions of the anomaly.

Results of the delineation surveys should be presented in a format that emphasizes size, geometry, and location of cavities or other structures producing the geophysical anomalies. Interpreted results of pole-dipole resistivity surveys are particularly well suited for this purpose. Figure 4.16, from the report by Fountain, et al. (1975),

TABLE 4-2

CANDIDATE GEOPHYSICAL METHODS FOR CAVITY DELINEATION PROGRAM
(DETAILED OR HIGH-RESOLUTION SURVEYS)

Most-Promising

Crosshole Radar

Pole-Dipole Electrical Resistivity Surveying (Bristow-Bates)

Acoustic Resonance (Subsurface Source)

Crosshole Seismic Method

Microgravimetry

Borderline

Constant Spacing Seismic Refraction

Seismic Reflection

Surface Ground-Probing EM (Radar)

illustrates a three-dimensional portrayal of three resistivity profiles crossing approximately perpendicular to the trend of a cavity system. The results of crosshole seismic and EM (radar) surveys, such as shown in Figure 4.11, can similarly be presented to give three-dimensional views of the cavity system. Results of a high-resolution microgravity survey of an anomaly discovered during a reconnaissance microgravity survey is illustrated in Figure 4.17, where a subsurface quarry system is shown to be well defined in plan (Neumann, 1977). To add depth information to the results shown in Figure 4.17 would require some borehole information for any of the negative regions of the contour plot. Realistic assumptions regarding geometry and rock density would also allow depth computations.

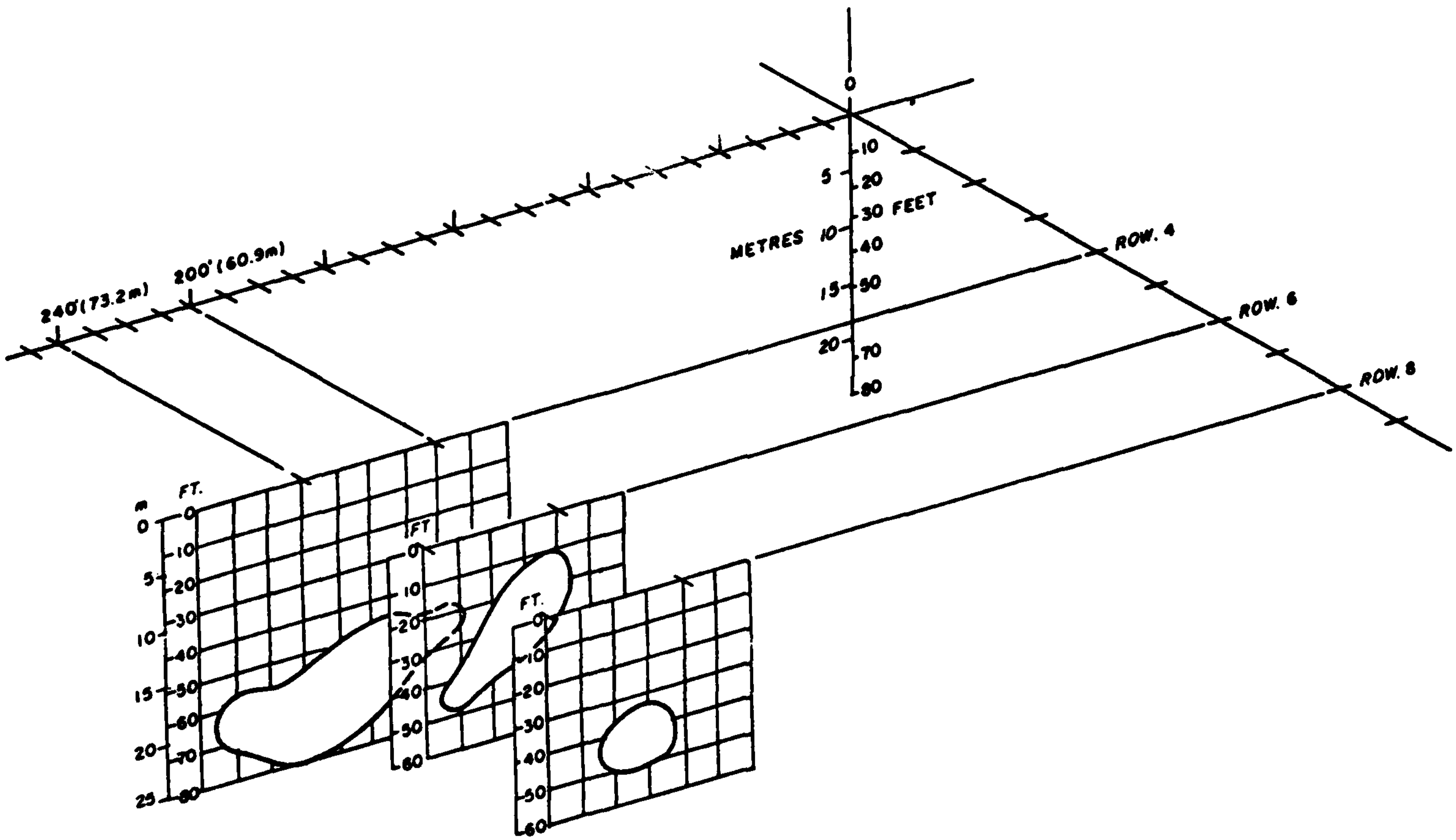


Figure 4.16. Three dimensional portrayal of the results of three parallel pole-dipole resistivity profiles crossing a large cavity (Fountain, et al, 1975)

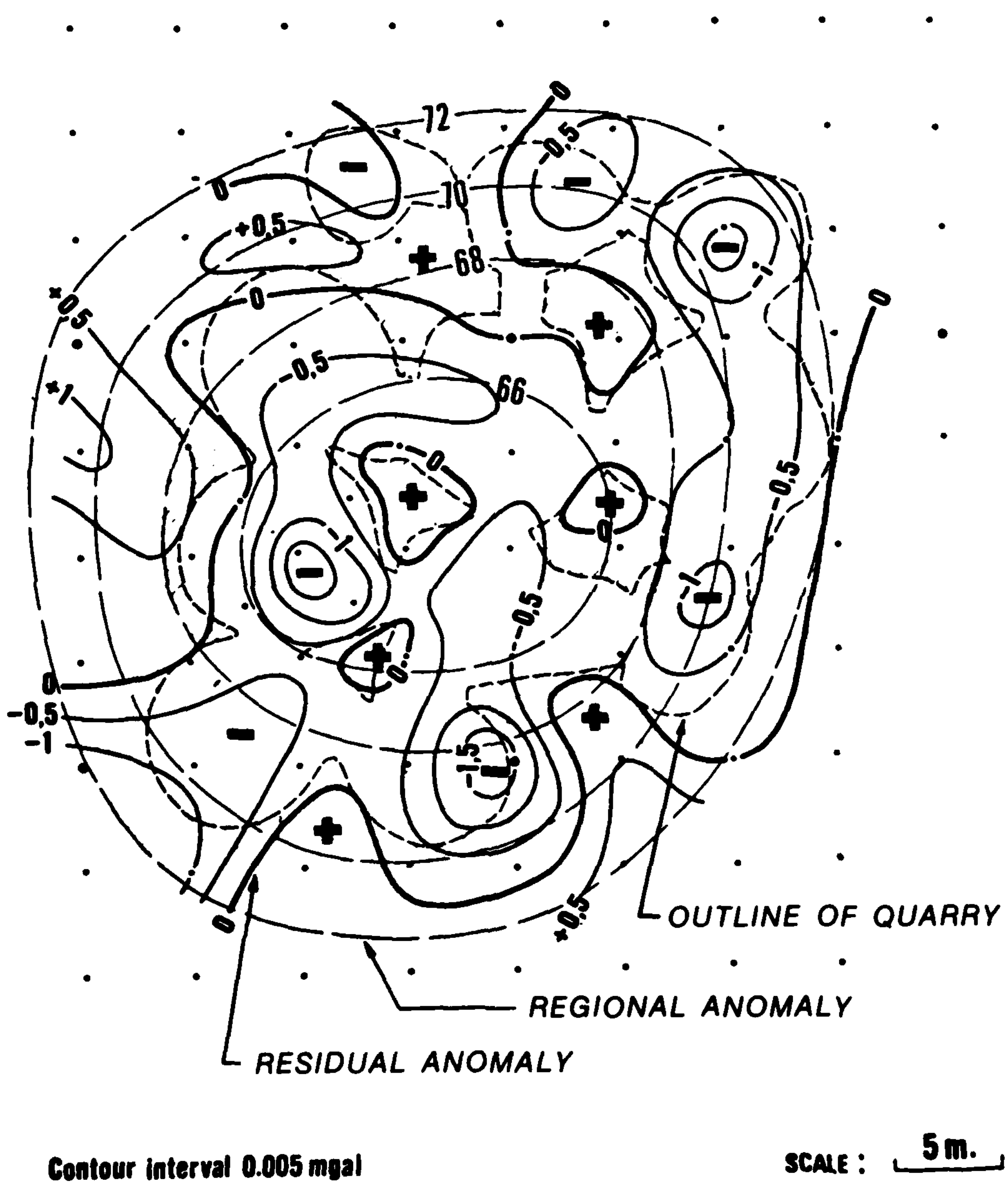


Figure 4.17. Residual gravity anomaly map over subsurface quarry illustrating complete definition of the system by a microgravity survey (Neumann, 1977)

CHAPTER V: EVALUATION OF FOUNDATION CONDITIONS

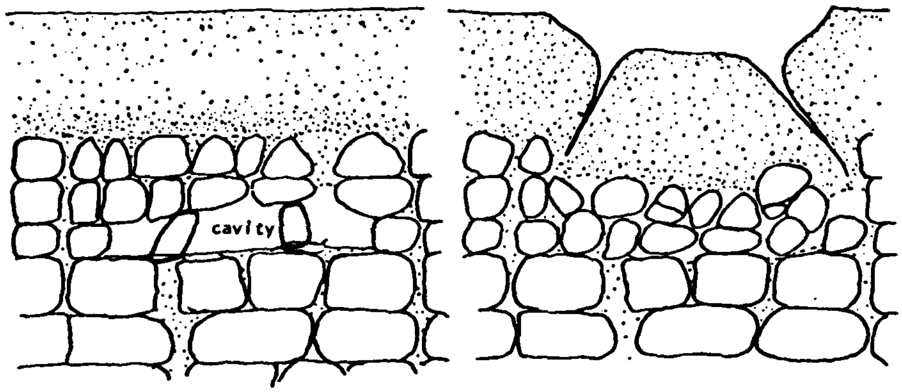
NATURE OF HAZARDS

The potential for surface collapse caused by sinkholes in karst terrain or subsidence and possible collapse in areas over mined openings can seriously endanger the safety of foundations. A thorough evaluation of well defined subsurface conditions in these two areas is critical in determining the potential hazards and their effects on foundation safety. The mechanics of sinkhole development, contributing factors, effects of mined openings, hazardous cavity conditions and techniques for evaluation of foundation safety are discussed in this chapter.

Solution Cavities and Sinkholes

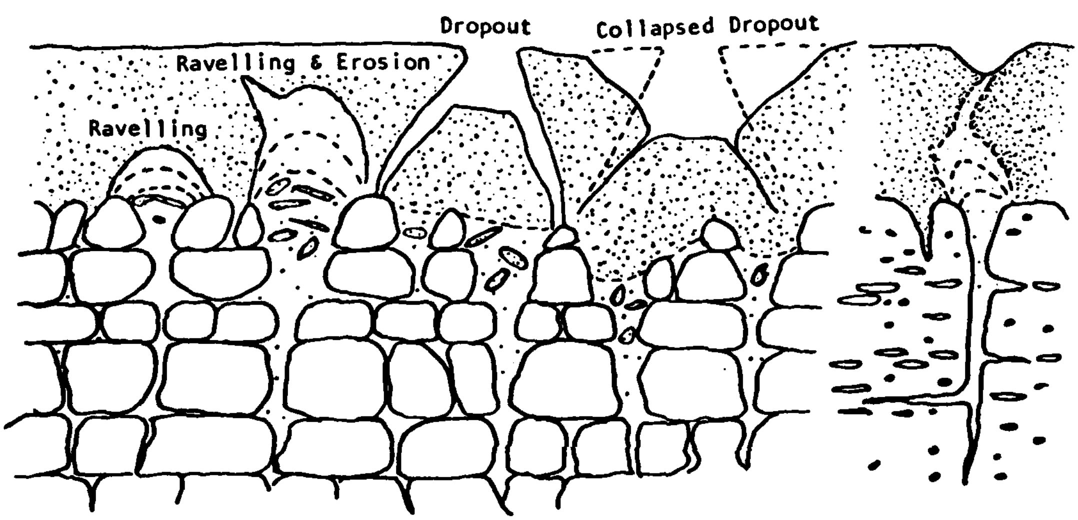
Collapse mechanisms

An understanding of the mechanisms of sinkhole development and contributing or modifying factors is essential in evaluating the degree of hazard. The development of sinkholes, often by sudden collapse of the ground surface, is related to stratigraphy, groundwater lowering, and erosion of overburden soils into solution features. The collapse of overburden and rapid development of sinkholes in limestone terrain is described by Sowers (1975, 1976a,b,c) and illustrated in Figure 5.1. Roof collapse of cavities near the bedrock surface by increased solution or increased roof loading results in dropout of shallow overburden (Figure 5.1a,b). While solution enlargement of cavities and weakening of the roof structure is a relatively slow process, collapse occurs suddenly. Sinkhole enlargement, sometimes to several hundred feet in diameter, progresses rapidly by erosion of overburden soils into open voids by surface drainage, especially during heavy rains. However, the most common development of sinkholes endangering structures is the collapse of cavities in relatively thick cohesive soil overburden (Figure 5.1c). Downward seepage causes progressive ravelling and erosion



a. Cavity in Rock produced by solution along joints and bedding surfaces

b. Collapse of rock cavity followed by dropout of residual soil above.



c. Stages in ravelling into enlarged joints by roof spalling and soil erosion

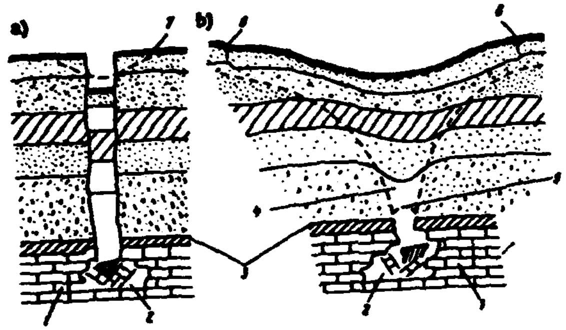
d. Sand ravelling into chimney fissure

Figure 5.1. Collapse mechanisms and sinkhole development (Sowers, 1975)

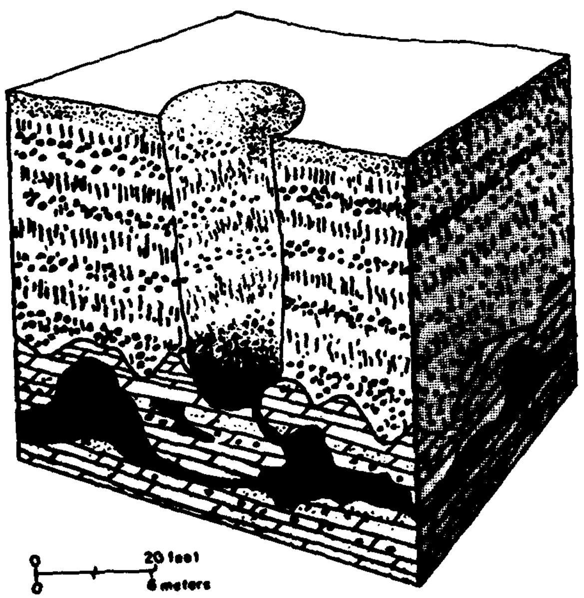
of cohesive soils bridging solution slots or fissures in the limestone bedrock. Upward enlargement of the soil cavity, to a diameter sometimes larger than 100 ft in clays, continues as long as eroding soil is carried away by circulating groundwater in bedrock openings. Otherwise, the process stops by clogging of openings with soft, wet soils. Roof collapse, forming a dropout, occurs when the roof load exceeds the shear strength of the roof soil. In sandy soils (Figure 5.1d) sand ravelling into solution fissures progresses into funnel-shaped surface depressions that may be over 100 ft in diameter.

Sinkhole pipes and filled sinks

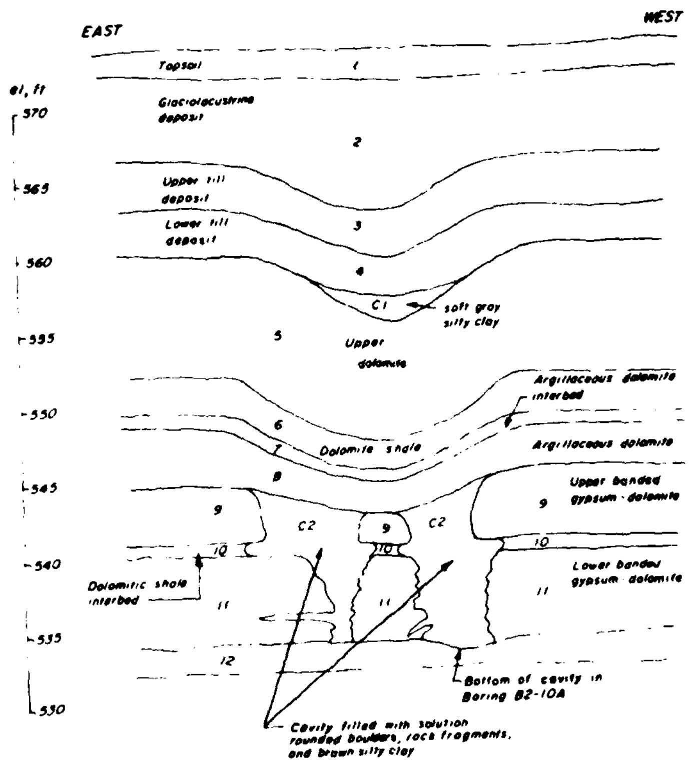
In sedimentary deposits, roof collapse of limestone cavities can lead to sinkhole pipes or depressions (Figure 5.2a), depending on the strength and vertical erosion susceptibility of overlying strata. Sinkhole pipes in Missouri (Figure 5.2b) described by Williams and Vineyard (1976) occur by downward solution of limestone, dolomite, and gypsum and upward progressive ravelling and erosion of residual soil. Collapse sinks are rare in an overburden thickness less than 12 ft. A thick soil cover of 40 to 100 ft promotes solution of bedrock by a lowered pH (4 to 5) of the groundwater. Open pipes often exist to within several feet of the ground surface with no apparent surface evidence. Excavation for a theater at Fort Leonard Wood, Missouri, revealed a vertical pipe shaft 75 ft deep in residual soil that had progressed by gravity stoping to within 7 ft of the ground surface. Surface depressions result from incomplete sinkhole development caused by resistant strata such as a thick clay layer or sedimentary rock layers. Cavity roof collapse and erosion of overlying sands of a lower aquifer (Figure 5.2a) forms a soil cavity protected against further vertical percolation from the upper sand aquifer by an intermediate impervious clay layer. A zone of expanded soil and deformed layers forms above the cavity roof. The surface depression can fill with water and soft sediments. An example of a filled cavity in gypsum-dolomite and deformed dolomite-shale, solomite, and till layers, filled in to a level surface, is shown in Figure 5.2c. This section was defined by explorations at the Davis-Besse Nuclear Power



a. **Characteristic deformations of the surface of karst-piping origin in Moscow. a) Open karst pipe; b) saucer-shaped sink of ground surface; 1) limestones; 2) karst cavity; 3) confining bed; 4) zone of expanded soil; 5) primary roof; 6) fissures in soil; 7) secondary form of surface after vertical collapse.** (Dykhovichnyi and Maksimenko, 1979. Copyright, Plenum Publishing Corp. Reprinted by permission.)



b. Sinkhole pipe collapse, Missouri uplands and valleys (Williams and Vineyard, 1976)



c. Filled sink depression in dolomite, northwestern Ohio (Millett and Moorhouse, 1973)

Figure 5.2. Development of sinkhole pipes and surface depressions

Station, described by Millet and Moorhouse (1973). An example of complex solution features, generally filled with stratified sandy silt, is shown in Figure 5.3. Extensive grouting during the initial remedial treatment of the embankment foundation at Wolf Creek Dam, Kentucky, defined extensive solution zones to a maximum depth of approximately 50 ft below bedrock surface and caverns with maximum heights of 20 ft. A concrete cutoff wall was finally used to prevent seepage erosion of soils beneath the dam. Geologic conditons at this site are further described by Kellberg and Simmons (1977).

Solution of evaporite deposits can also cause potential collapse problems. For example, the Hutchinson salt member of the Wellington formation in Kansas is a potential problem along a solution front and in areas of faulting, and in the Paradox Basin, salt solution related to salt anticlines is of major concern (Hambleton, 1980).

Contributing or modifying factors

Lowering of the groundwater level is a major cause of sinkhole occurrence, as illustrated in Figure 5.4. Groundwater lowering within the overburden increases the effective weight and potential for collapse. Other effects of groundwater lowering include the following (Sowers, 1975):

a. Increased downward seepage gradients and accelerated downward soil erosion.

b. Reduced capillary tension in cohesionless sands and increased ability to flow through narrow openings.

c. Shrinkage cracking in highly plastic clays that weakens the mass in dry weather and produces concentrated seepage during rains.

Channeling of surface drainage into depressions accelerates ravelling and erosion of soil cavity roofs with increased occurrence of dropouts. Causes of sinkhole collapse in Missouri, summarized in Figure 5.5, indicates that altered drainage was the major cause of sinkhole collapse. Soil type has a major effect on collapse. Silts and silty clays are easily eroded and subject to collapse. Plastic clays are more resistant to erosion and less likely to collapse.

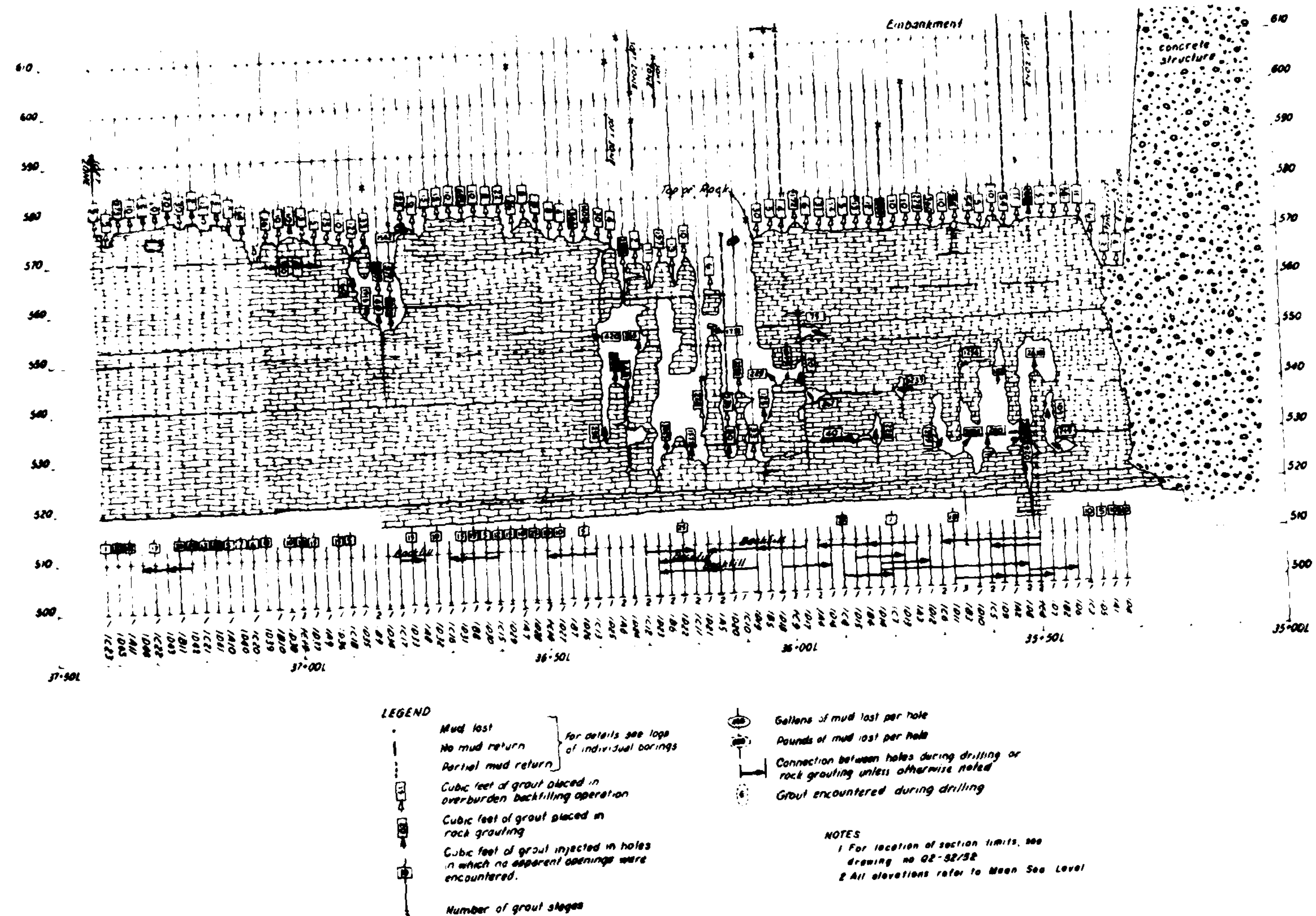
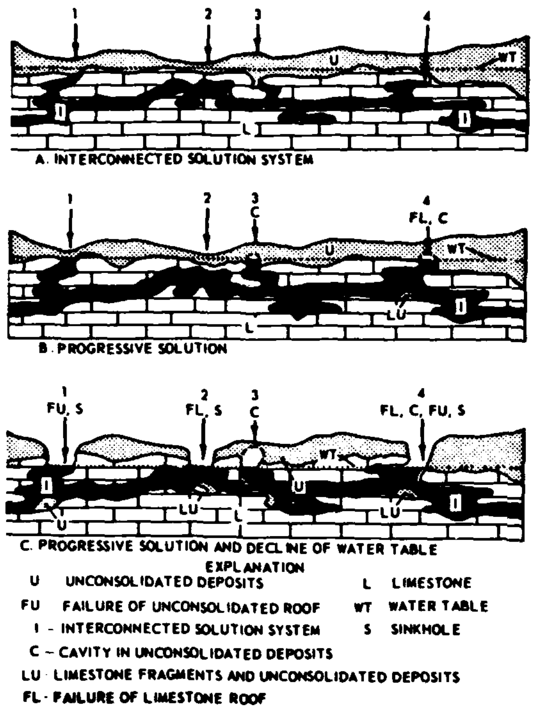
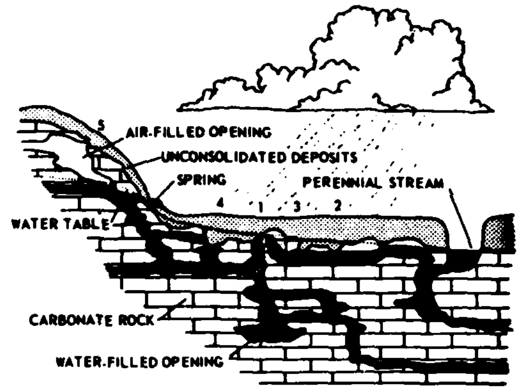


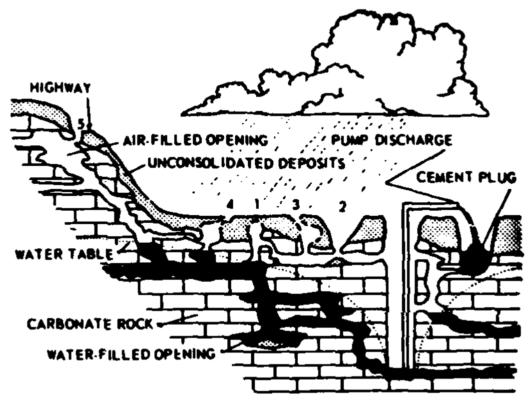
Figure 5.3. Example of complex solution openings along joints in argillacious limestone, Wolf Creek Dam, Kentucky (U.S. Army, 1975)



a. Natural sinkhole development, Alabama (Newton, 1976)

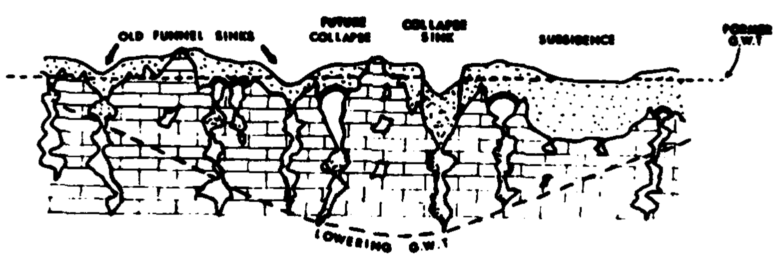


1. Before groundwater lowering



2. After groundwater lowering

b. Man-induced sinkhole development, Alabama (Newton, 1976)



c. Subsurface conditions, Hershey Valley, Pa. (Foose and Humphreville, 1979)

Figure 5.4. Effect of groundwater table lowering on sinkhole development

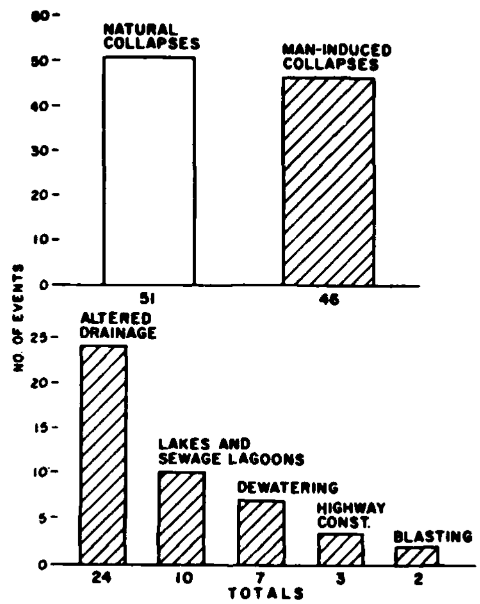


Figure 5.5. Causes of sinkhole collapse in Missouri, based on records since 1930 (Williams and Vineyard, 1976)

The subsurface stratigraphy also has a major effect on the occurrence of sinkholes. Solution-prone limestone beneath Kansas City is protected by thick strata (averaging 14 to 18 ft) of impermeable shales, and mined rooms, 12 to 13 ft high, with clear spans of 30 ft, are used extensively for storage and office space by industry (Stauffer, 1977). In the USSR, stratigraphic conditions are used in classification of potentially hazardous conditions. Subsurface conditions classified as dangerous in the Moscow area (DyKoukhnyi and Maksimenko, 1979) include absence or weak development (7 to 10 ft thick) of confining clay beds at the limestone bedrock surface. Those classified as potentially dangerous include the presence of confining clay beds up to 30 ft thick.

Subsidence and Collapse Over Mined Openings

Mechanisms of failure

Subsidence and the formation of sinkholes above abandoned mines presents the greatest hazard, in terms of severity of damage, to foundation safety. According to Gray (1976), numerous abandoned coal mine workings exist in the anthracite fields of eastern Pennsylvania and the bituminous fields of the Appalachians, the Illinois basin, the Rock Springs area of Wyoming, and other areas of the United States. Wide variations in room-and-pillar patterns and percentages of coal extracted have produced wide variations in the long-term stability of pillars, mine floors, and mine roofs. The progressive deterioration of pillars, floors, and roofs by exposure to air and water has resulted in collapse of strata over mine entries, progressive crushing of pillars, and bearing failure of mine floors and soft strata beneath pillars. The resulting collapse causes differential strains and settlements, depression troughs, cracking, and sinkholes in the ground surface above the mine. The formation of sinkholes may be sudden, especially above shallow mines, where the entire mine roof section fails and overlying soils fall into the void. Sinkholes can also develop slowly by progressive caving of the mine roof extending to the ground surface. Surface subsidence and sinkholes can occur many years after mining has ceased (Carter, et al., 1980; Bruhn, et al., 1980).

Sinkholes and subsidence troughs

Gray, et al., (1977) have summarized the occurrence of sinkholes and troughs over abandoned mines in the Pittsburgh coal region of Pennsylvania, Maryland, West Virginia, and Ohio. Their study of 352 subsidence incidents, occurring from 1955 to 1976, mainly in Allegheny County, Pennsylvania, provide an insight into the character of subsidence in relation to overburden thickness for some 200 incidents.

Kind and depth of subsidence. Approximately 90 percent of the incidents were sinkholes and 10 percent were subsidence troughs. The known depth for 187 incidents, shown statistically in Figure 5.6, ranged up to

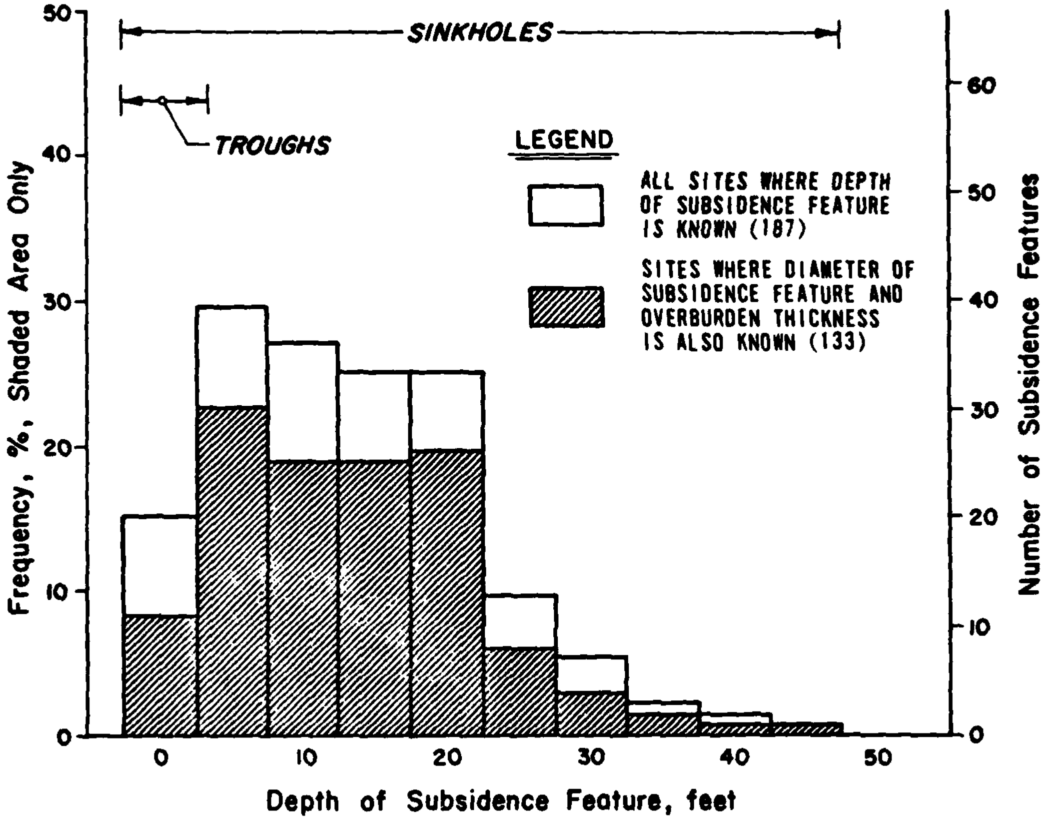


Figure 5.6. Depths of subsidence features (Gray, et al., 1977)

45 ft for sinkholes and to 3 ft for troughs. The predominant depth of sinkholes ranged from 5 to 20 ft.

Effect of overburden thickness. Data for 125 sinkholes and 15 troughs above abandoned mines, shown in Figure 5.7, indicate that sinkholes occur with overburden thickness (soil and rock) up to 200 ft, with maximum diameter of 40 ft. Troughs as large as 1600 ft in mean diameter occur in overburden thicknesses up to 325 ft. The curves in Figure 5.7 relate trends in mean surface diameter to overburden thickness. The frequency chart shown in Figure 5.8 indicates frequent sinkhole occurrence for overburden thickness up to 50 ft, a substantially smaller frequency for depths up to 100 ft, and infrequent occurrence for greater depths. Several sinkholes were documented in overburden thicknesses of 80 to 150 ft.

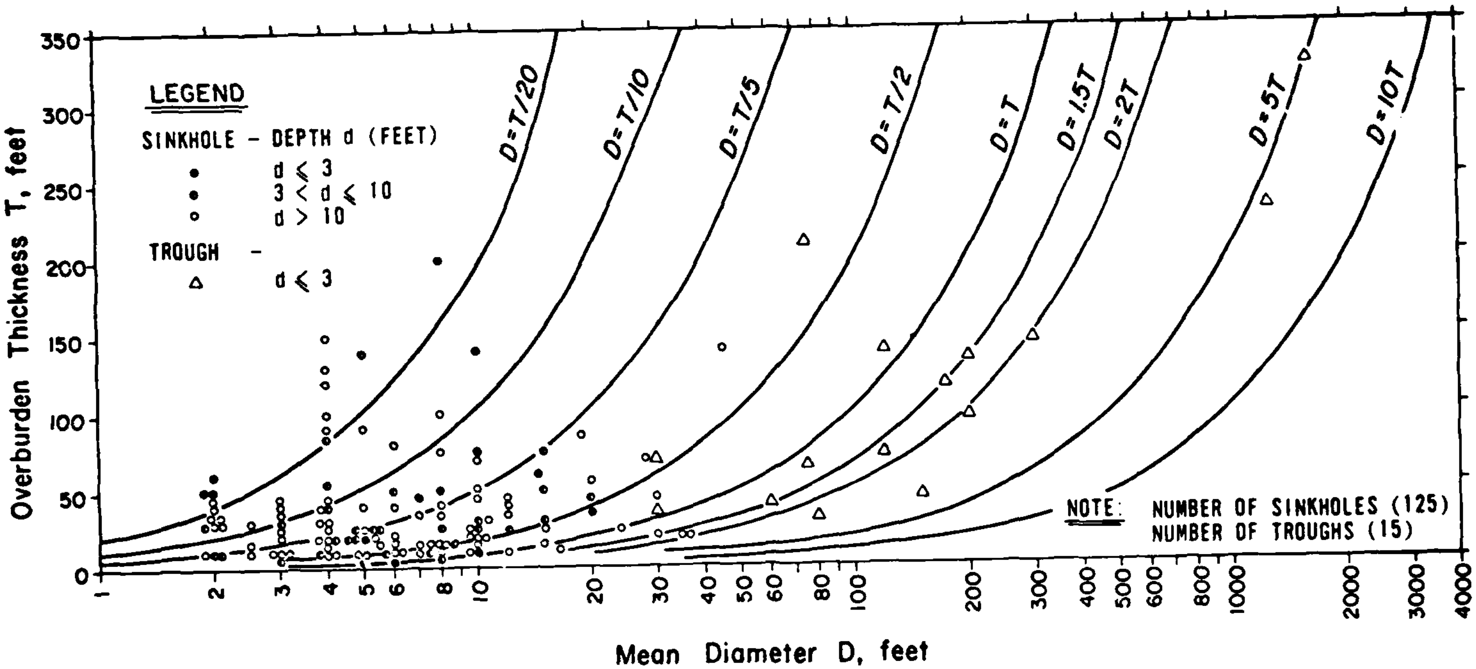


Figure 5.7. Relationship of diameter and depth of subsidence to overburden thickness (Gray, et al., 1977)

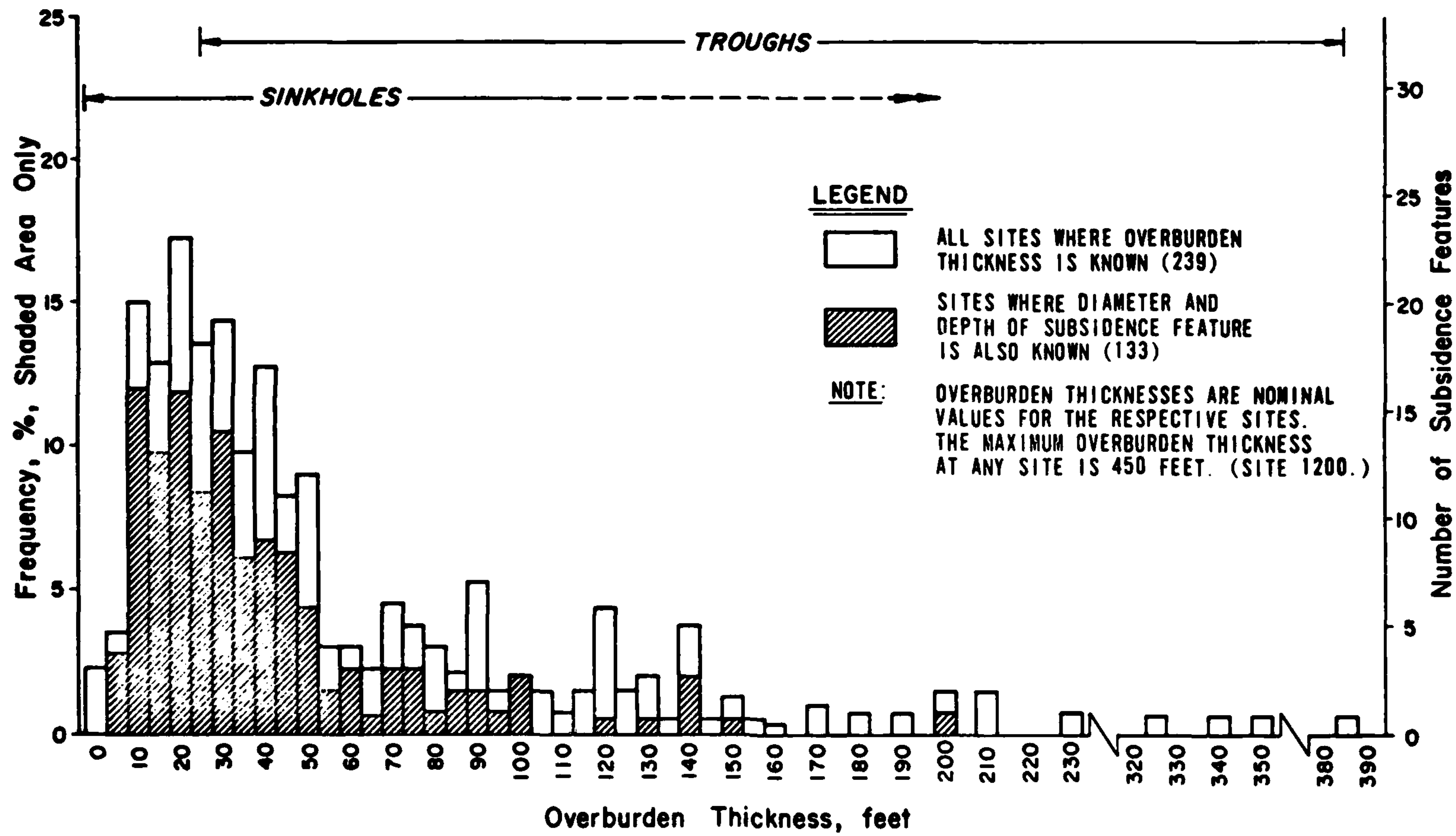


Figure 5.8. Overburden thickness at sites of subsidence (Gray, et al., 1977)

Adverse jointing or room width greater than the normal 20 ft were cited as two possible causes. Another cause was a soil overburden thickness greater than the typical 10 to 15 ft which is less capable of spanning a collapse cavity progressing upward through the underlying rock strata. No subsidence has been documented above an abandoned mine where the overburden thickness exceeds 450 ft. Based on present concepts of subsidence mechanics, however, the 450 ft overburden thickness should not be regarded as a maximum upper limit.

Time of occurrence. Sinkholes and troughs above abandoned coal mines can occur 100 or more years after mining stops. Cumulative occurrence interval curves in Figure 5.9 show that 60 percent of the 76 documented sinkholes occured 47 or more years after mining while 60 percent of the 15 documented troughs occurred 30 or more years after mining. Sinkholes were sometimes associated with troughs, indicating sinkhole development by erosion of subsurface soils following initial subsidence.

Effect of precipitation. In the steeply dipping anthracite coal beds of eastern Pennsylvania, periods of high precipitation from 1950 to 1973 were followed by increased subsidence. Seepage pressures from water percolating down the steeply dipping coal beds also caused blowouts in valley slopes or river beds, followed by inrush of soil from above and surface subsidence. In horizontal strata in the bituminous coal region, mines of depths up to 100 ft were usually wetter, and high precipitation since mining stopped is associated with high frequency of sinkholes. Sinkhole development in the Pittsburgh Coal region was related to seepage in three main ways:

a. Increasing moisture contents of the soil and rock which decreased their strengths.

b. Increased slaking, swelling, and shrinkage of soil and rock and oxidation of minerals, particularly by alternate wetting and drying.

c. Development of seepage water pressure in overburden that reduced the frictional resistance between rock blocks.

Types of overburden strata. In the area of the Pittsburgh Coal Region where sinkholes have been identified, predominant rock sequences

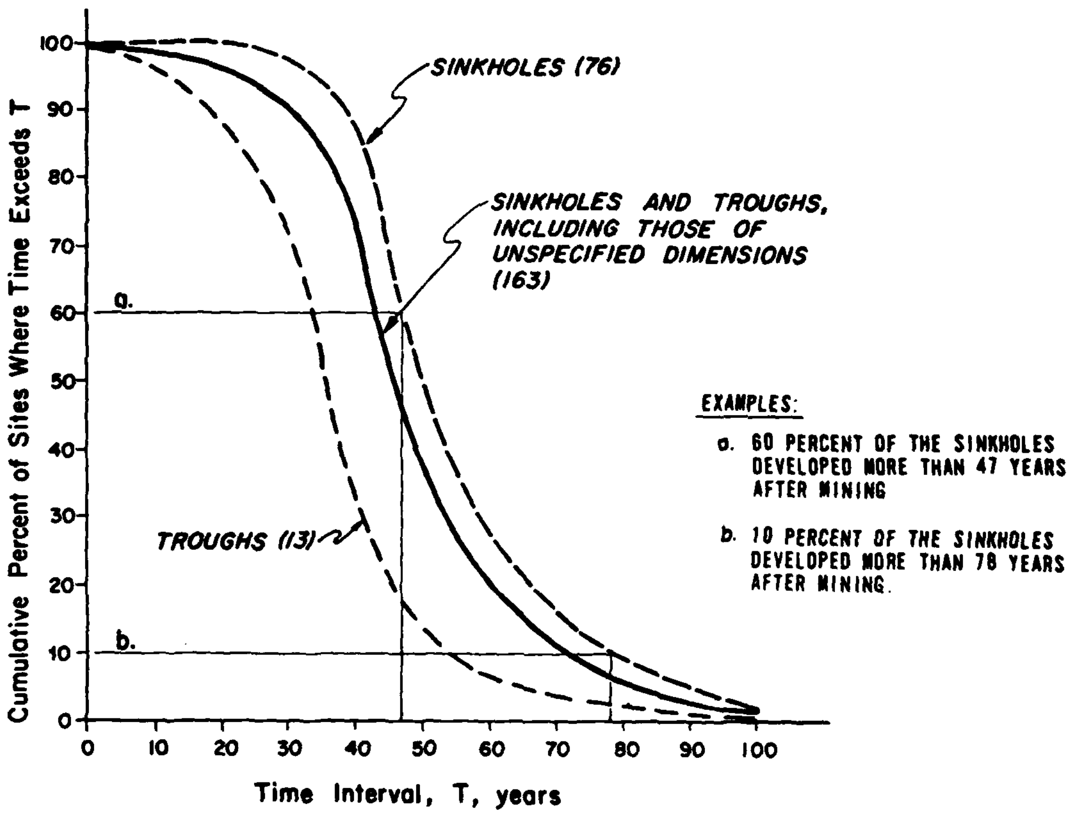


Figure 5.9. Minimum time interval between mining and subsidence (Gray, et al, 1977)

are either interlayered shale, claystone, and limestone or interlayered shale, claystone, and sandstone. Shale and claystone appear to be most prominent in sinkhole areas. This rock type reflects to a degree the sort of weatherability and strength losses asso ated with cyclic percolation of seepage water discussed in the previous paragraph. Conversely, limestone strata dominate in the first 50 to 100 ft in West Virginia and Ohio and exhibit much less strength loss and weatherability than do shale and clay strata when subjected to cyclic seepage of water. Fewer sinkholes are expected in limestone areas, but data are unavoidable for corroboration.

Subsidence troughs. Subsidence of the ground surface over mines creates mainly circular (sometimes slightly elongated) troughs, regardless of mine depth. The main hazard is from differential horizontal and vertical movements of the ground surface, as shown in Figure 5.10. In the Pittsburgh Coal Region, Gray, et al., (1977) found maximum subsidence of 2 to 3 ft when the length of unsupported seams reached 1.5 to 1.6 times the overburden thickness. They indicate that maximum subsidence can reach 75 percent of the seam thickness in total extraction mining. Subsidence troughs above abandoned room and pillar coal mines can originate from three types of failures, acting singly or in combination:

a. Caving of mine roof between pillars

b. Crushing of pillars

c. Punching of pillars into mine floor

Gray, et al., (1977) indicate that the latter two mechanisms predominate in the Pittsburgh Coal Region for troughs larger than 30 ft in diameter where mine cover was greater than 50 to 60 ft. Otherwise, troughs were usually associated with sinkholes where caving was the predominant mechanism.

The maximum size of troughs resulting from crushing of pillars can be estimated as shown in Figure 5.11. In the Pittsburgh Coal Region sedimentary deposits, the angle of draw (β) ranges from 15 to 27 deg. In overburden soils, the angle of draw ranges from 30 deg for fine grained soils to 45 deg for coarse grained soils. Attewell and Farmer

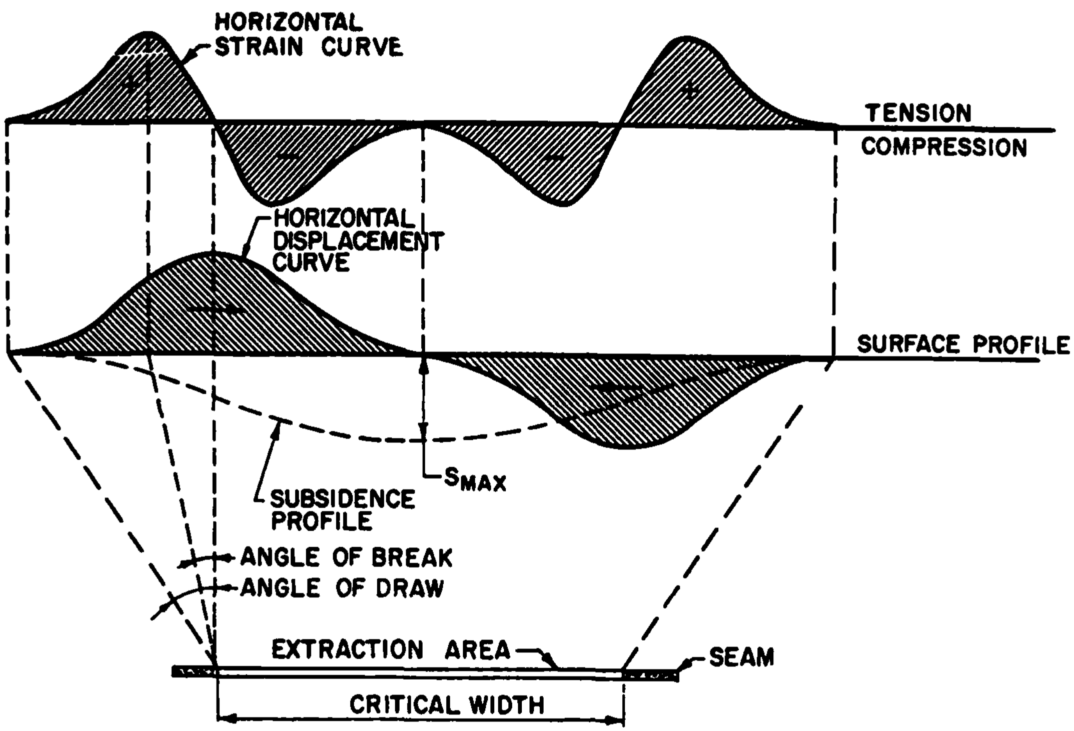
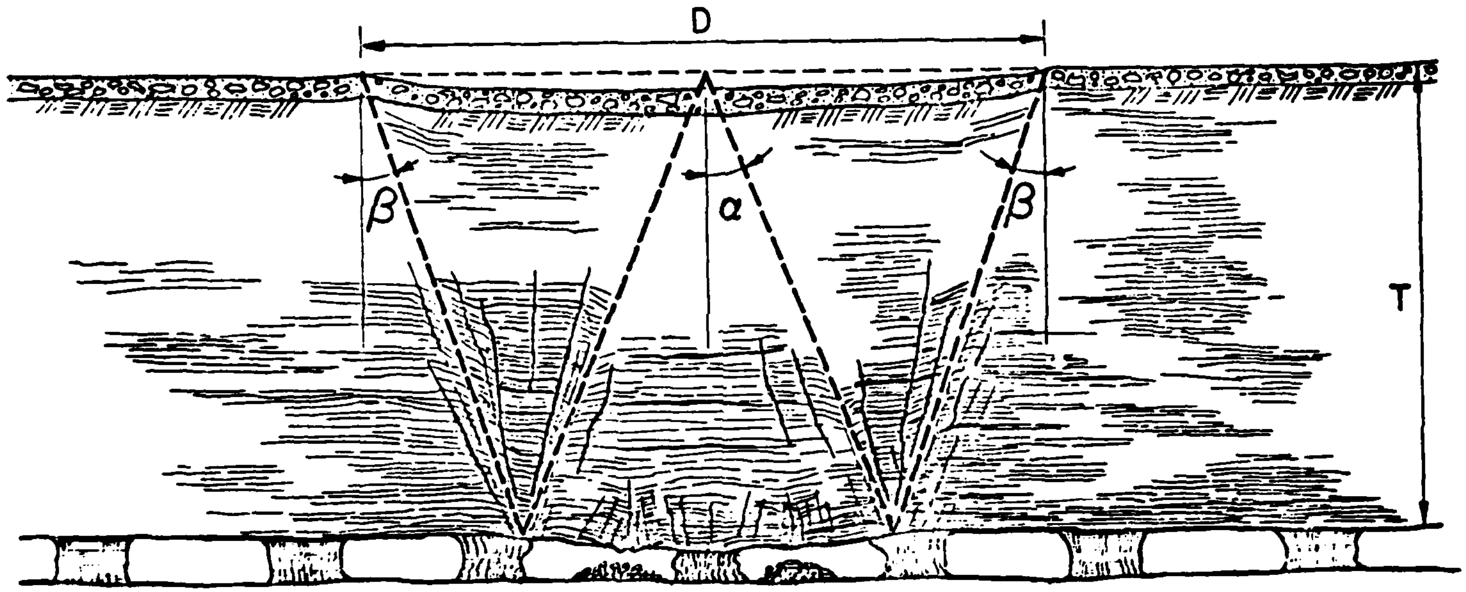


Figure 5.10. Differential deformations caused by subsidence (Gray, et al., 1974)



$$D = 2T(\tan\alpha + \tan\beta)$$

Figure 5.11. Relationships of trough diameter, overburden thickness, and angles of break and draw for trough subsidence above abandoned mine in Pittsburgh coal region due to pillar failure (Gray, et al., 1977)

(1976) indicate that the angle of draw is approximated by $45-\phi/2$ deg. (This angle applies to soil.) Gray, et al., (1977) indicate that the angle of break (α) is of the order of 22 to 24 deg. Punching of pillars into mine floors can be extensive when flooding softens underclay floors. The relation of bearing capacity to underclay shear strength is shown in Figure 5.12. Troughs from pillar failure may occur several decades after mining, while troughs related to pillar punching generally occur within 10 to 15 years after mining. A comprehensive discussion of subsidence and caving is also given by Obert and Duvall (1967).

Site geologic conditions (jointing, faults, stratigraphy, groundwater levels) and mine conditions have a significant influence on the magnitude of surface subsidence displacements and maximum vertical settlement. Prediction methods for subsidence over steeply dipping mined seams have been developed (Brauner, 1973, and Hiramatsu, 1979). However, in most instances field data is insufficient to verify the accuracy of these methods. Charts for estimating subsidence and damage (Shadbolt, 1978) developed by the British Coal Board apply mainly to longwall mining and are not applicable to the room and pillar mines prevalent in the United States.

Mining of dipping ore bodies can also cause large surface subsidence. Metsger (1979) describes subsidence events and sinkholes in the karst valley at the reopened Friedensville zinc mine in the Saucon Valley of eastern Pennsylvania. Stope mining to depths of 1000 ft, using 25-ft benches downdip, large rooms and pillars, and extensive pumping for dewatering, resulted in a series of subsidence events. In one event, on 27 March 1968, a block of ground 700 by 350 ft wide and 600 ft thick suddenly dropped 21.5 ft. This event occurred over a long abandoned portion of the mine and was equivalent in energy released to an earthquake of about magnitude 3 on the Richter scale. From data accumulated over 14 years, it appeared that the new mining activity had resulted in two sets of vertical joints that developed into faults around a massive block some 400 ft deep above the older mine workings. As an example of the severity of problems that can occur in karst terrain, Metsger also

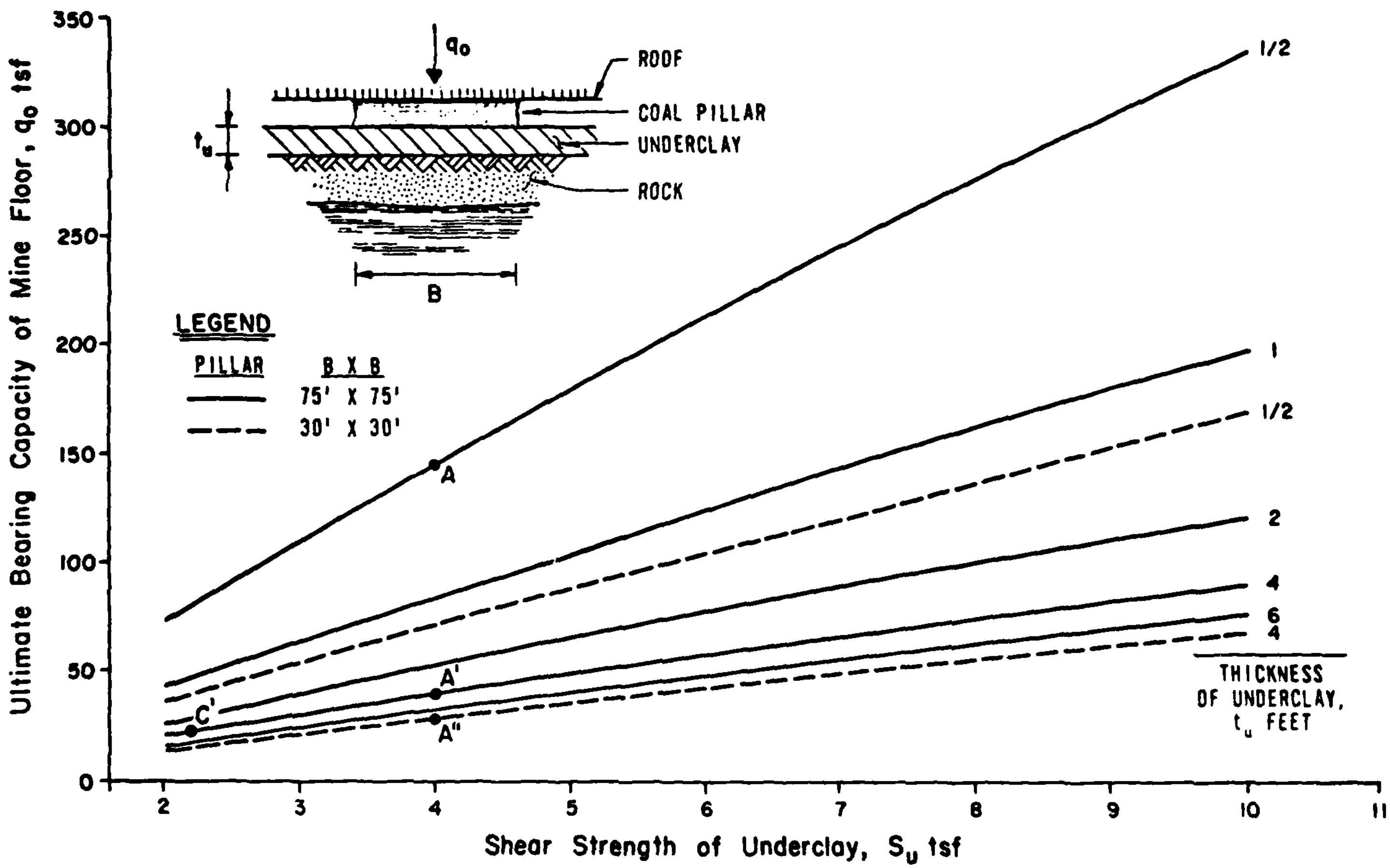


Figure 5.12. Bearing capacity of mine floor (Gray, et al., 1977)

describes the use of sinkholes for mine waste discard and development of other sinkholes in a lagoon and a tailings disposal pond. The discharge and escape of mine waste into sinkholes would have a great influence on groundwater chemistry. Heavy rains, especially during a hurricane, caused massive recharge of subsurface water through sinkholes and diversion of a local stream into underground solution channels. The stream bed finally was repaved to restore surface flow.

Mine roof caving

In discussing sinkholes, Gray, et al., (1977) present useful charts for estimating height of mine caving. Assuming a bulking factor of 10 to 12 percent for falling rock, charts shown in Figure 5.13 can be used to estimate the critical height of a mined opening for unrestricted roof caving and the maximum height of caving for a known angle of break. Diagram A of Figure 5.13 illustrates the effect of mined height and bulking volume for a constant angle of break. Diagram B of the figure relates height of caving to angle of break for different roof spans; Points A and B show the effect of angle of break on height of caving for a roof span of 20 ft and Points B and C show roof span effect for the same angle of break. A similar comparison is indicated for critical height by the Points A′, B′, and C′ in Diagram C. In discussing this chart, Gray, et al., point out that a mined height as small as 15 in. with an angle of break of 15 deg could result in unrestricted caving. The obvious unknown is the angle of break. Gray, et al., cite photo-elastic studies which indicate that the angle of break decreases as caving proceeds upward and reaches a minimum value of 10 to 15 deg. Cording, et al., (1971), in discussing underground rock caverns, suggest that for caverns below a ground surface depth greater than 3B, the apex angle of a triangular block above the cavern is equal to twice the angle of rock friction, ϕ . On this basis, α can be taken as roughly equal to ϕ . If weak or sheared shale or claystone existed above the opening with steep joints, ϕ and thus α could be as low as 15 deg. Conditions conducive to various modes of mine roof failure from Morgan (1973) are listed in Table 5-1.

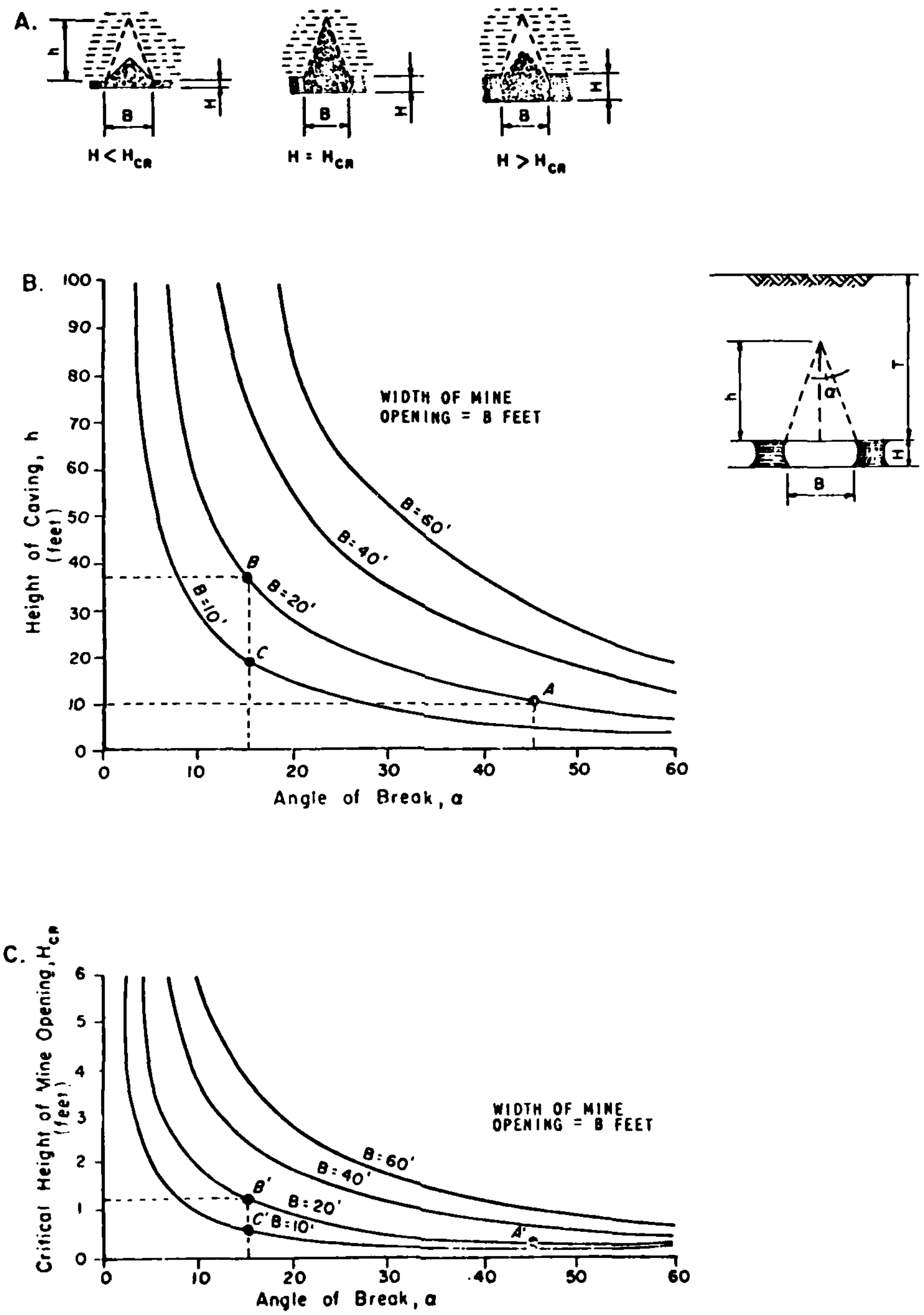


Figure 5.13. Relationship of height of caving to height and width of mine opening and angle of break (Gray, et al., 1977)

TABLE 5-1.

CONDITIONS CONDUCIVE TO THE DEVELOPMENT
OF VARIOUS MODES OF ROOF FAILURE

(After Morgan, 1973)

Conditions conducive to shear failure are:

1. A mine roof dissected by planes of weakness--joints, clay veins with slickensides, and so on--oriented so as to permit blocks of rock to slip out of place;

2. A great overburden thickness or high vertical stresses transferred from adjoining areas of the mine;

3. High horizontal stresses;

4. Wide spans;

5. Pillars and floor that are stiff compared to the roof; and

6. Soft shale located above a comparatively rigid mine roof.

Conditions conducive to flexural failure by loading in a vertical plane are:

1. Low ratio of horizontal to vertical stresses;

2. Thinly bedded layers or layers that have separated along horizontal planes;

3. Wide spans;

4. Jointing in the roof or coal;

5. Pillars and/or floor of low stiffness; and

6. Roof layers of low stiffness.

Conditions conducive to flexural failure by buckling are similar to those for flexural failure above, except that the ratio of horizontal to vertical stresses is higher.

Caving has also been related to height of mined opening. Piggott and Eynon (1978) present diagrams showing the relationship between bulking factor and maximum height of collapse for rectangular, wedge, and conical shapes, as shown in Figure 5.14. They conclude, on the basis of experience from ancient shallow mine workings, British longwall mining, and current Australian and American room and pillar mining, that hazardous conditions exist where old mine workings occur at depths less than 10 times extraction thickness below the bedrock surface.

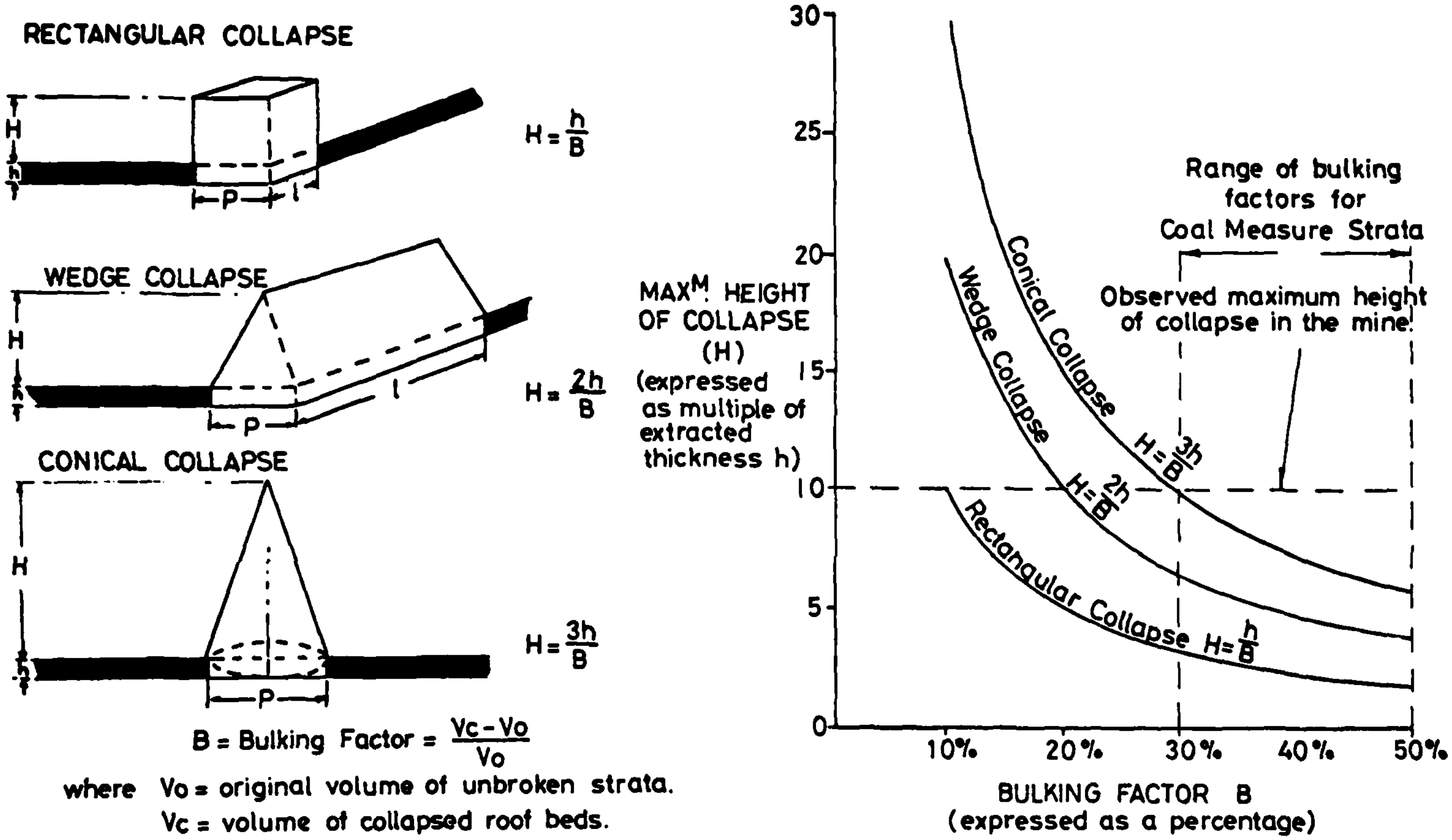
Collapse Potential from Other Types of Mining

The potential for collapse of the ground surface above mined evaporite deposits, particularly salt, is a major hazard in certain areas. Underground or hydraulic mining of salt can lead to collapse of the ground surface. Terzaghi (1969) describes a large collapse zone resulting from brine extraction from salt deposits located at depths in excess of 1000 ft at Windsor, Ontario. Corrosion of casing through salt has caused significant surface collapse in many places in Kansas and elsewhere (Hambleton, 1980). Other mining activities such as abandoned lead-zinc mines in the Tri-State area of Kansas, Missouri, and Oklahoma have caused collapse problems which are currently under study by the U. S. Bureau of Mines (Hambleton, 1980).

CRITICAL DEPTH AND SIZE OF OPENINGS

Natural Cavities

Considerable information exists on hazardous cavity conditions in overburden soils, as described earlier in this chapter. However, very little information is to be found on the stability of natural cavities below bedrock surface. One criterion used for building foundations in the Hershey, Pennsylvania area, is an intact noncavernous depth of 8 ft below drilled caissons (Foose, 1979). Loads of 20 tons per sq ft were



a. Diagram showing notation for calculating maximum height of collapse (H) in relation to geometry of collapse.

b. Graph showing variation in maximum height of collapse for different modes of failure and bulking factors.

Figure 5.14. Height of collapse related to bulking factor (Piggot and Eynon, 1978.) Reprinted by permission of Pentech Press, Ltd.

used in calculations assuming various cavity sizes up to 50 ft and rock thicknesses of 15 ft above the cavity. The studies indicated that 8 ft of solid rock would provide a safety factor of 1.7.

Theoretical studies of openings in rock for coal gasification in sedimentary rocks, by Greenlaw, et al., (1977), provide some insight into minimum depths. Using Mindlin's (1940) closed form solution, charts were developed for circular tunnel openings in a homogeneous, isotropic, elastic medium. As shown in Figure 5.15, the stress ratio is related to the ratio of depth to tunnel radius (d/R ratio). Separate charts were developed for different values of K (the ratio of in situ horizontal stress to vertical stress) ranging from 0.2 to 1.0, and a constant Poisson's ratio of 0.3. Greenlaw, et al., state that the charts for the elastic cave are in agreement with finite element studies of an 80-ft-wide cavity at depths of 100 and 180 ft using in situ properties for two field sites. The charts can be used to determine the critical d/R ratio for no roof tension and a minimum depth for a given size of a tunnel-like cavity. No roof tension would imply a stable condition in competent rock (i.e., no adverse jointing or solution-widened joints). For example, no roof tension would occur at a K value of 0.4 and a d/R ratio greater than 2. This condition implies that a cavity with a radius of 20 ft at an overburden depth of 40 ft would be stable in competent rock. However, if the K value was 0.3, roof tension would occur for d/R values greater than 4, as indicated in Figure 5.16. This figure summarizes limiting roof tension angles for different K values.

Since roof tension is dependent on the in situ stress ratio, K , structure loading could decrease the value of K , as illustrated in Figure 5.17. In this example, the structure load reduces K from 0.4 to 0.3 and causes roof tension. In addition, block jointing and solution-widened joints above the cavity with roof tension could lead to roof collapse and possible hazardous seepage erosion conditions in the overburden. Carrying this approach one step further, for the structure loading and soil-rock conditions shown in Figure 5.17, a limiting depth for roof tension, assuming K reduced to a value less than 0.4, would be about 200 ft.

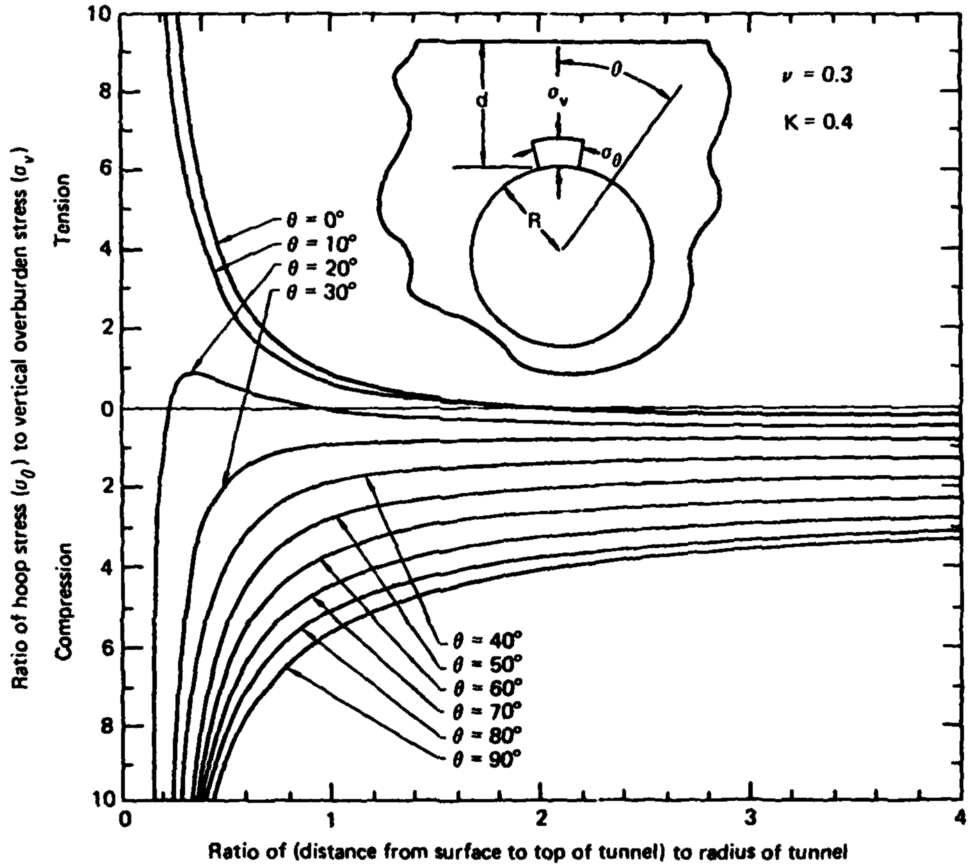


Figure 5.15. Stress in the roof of a circular tunnel at various angles (Θ) from the vertical. K = ratio of horizontal to vertical in situ stresses, ν = Poisson's ratio (Greenlaw, et al., 1977)

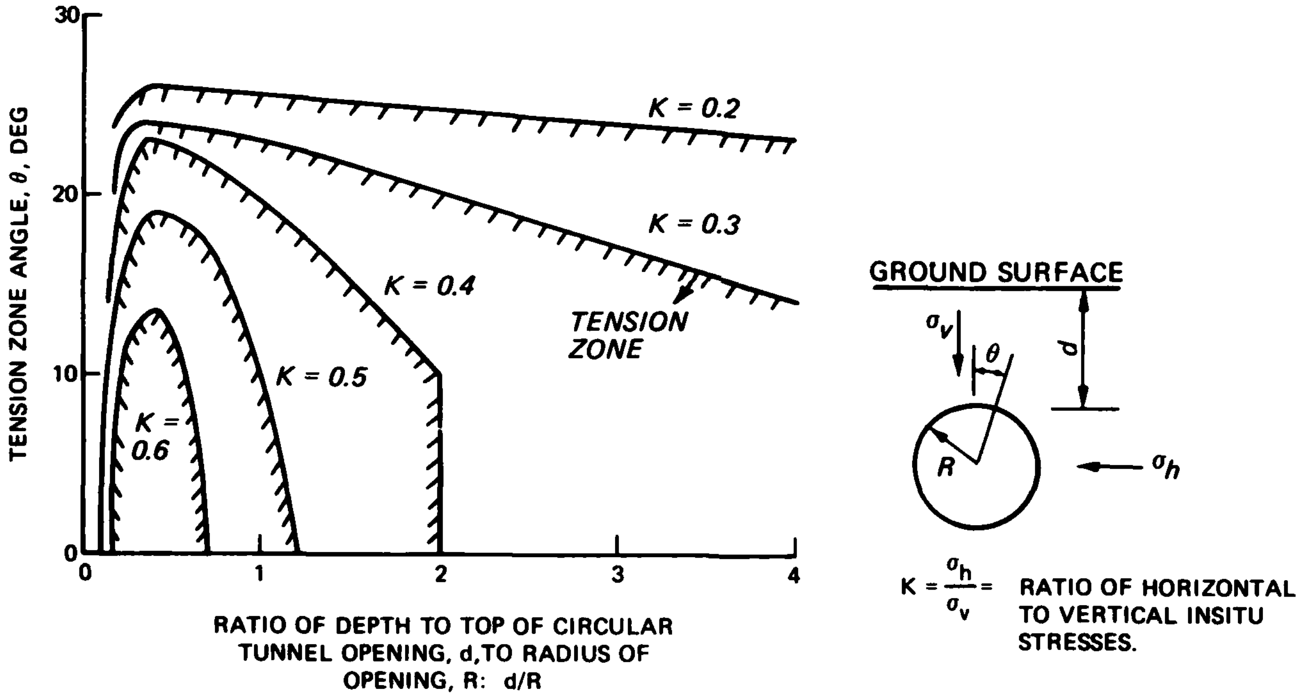
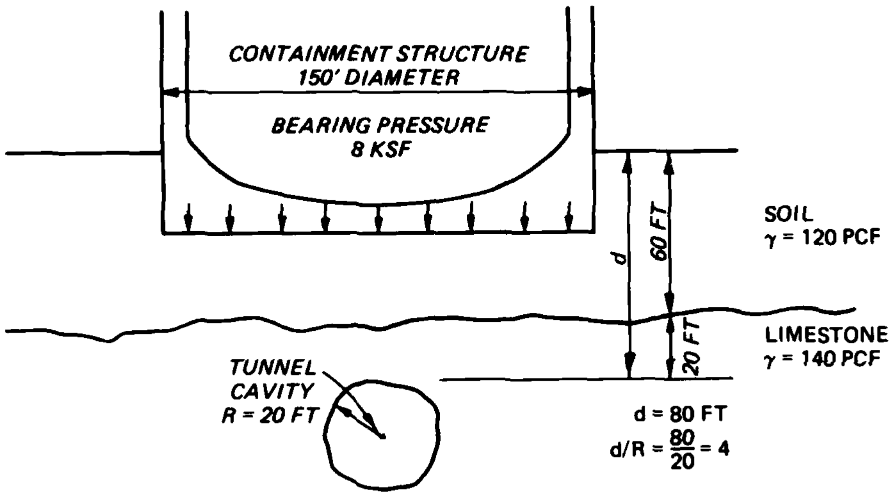


Figure 5.16. Tension zone around top of tunnel (after Greenlaw, et al., 1977)



ASSUME K BEFORE CONSTRUCTION ≈ 0.4 .
FOR THIS CONDITION, NO TENSION EXISTS
IN THE ROOF. AT DEPTH d:

$$\sigma_v = \frac{60 \times 120 + 20 \times 140}{1000} = 10 \text{ KSF}$$

$$\sigma_h = 0.4 \times 10 = 4 \text{ KSF}$$

AFTER CONSTRUCTION σ_v INCREASES FROM 10 KSF TO 13 KSF DUE TO STRUCTURE LOAD AND

$K = 4/13 = 0.3$

$\theta \cong 14$ DEG

FOR TENSION ZONE IN ROOF OF CAVITY.

DEPENDING ON JOINT PATTERN AND SOLUTION OF JOINTS, COLLAPSE ZONE COULD BE GREATER THAN SHOWN.

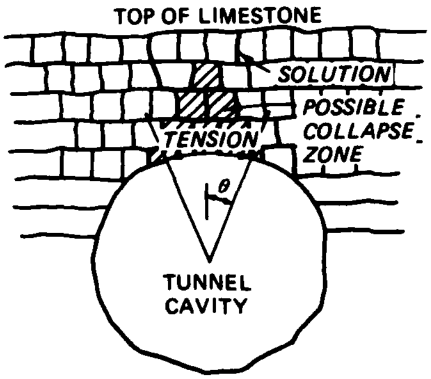


Figure 5.17. Hypothetical example of roof collapse into circular tunnel cavity

A theoretical study of the structural stability of circular tunnel cavities as large as 20 ft in diameter is described in the Preliminary Safety Analysis Report (PSAR) of the North Coast Nuclear Plant No. 1 site in Puerto Rico (USAEC, 1975). Two-dimensional finite element analyses for a cavity depth of 200 ft indicated a maximum shear stress increase of 20 percent for static structural loading and a 27 percent increase in principal stress difference ($\sigma_1 - \sigma_3$) due to pseudostatic loading for 0.35 g earthquake acceleration. Principal stresses were compressive and the results were considered conservative on the basis of linear elastic conditions.

The stability of conglomerate overlying karst caverns in Italy is reported by Capozza, et al., (1977). The maximum dimension of underground caverns that would be stable under foundation loads for a steam power plant was determined. The mechanical behavior of the conglomerate formation overlying caverns in limestone was determined from laboratory and in situ tests and observation and on the basis of back analyses of several existing caverns extending into the conglomerate. The analyses were performed using a finite element computer program, taking into account the low tensile strength of the conglomerate. The results of parametric studies varying the diameter of a cylindrical cavity (circular in plan view) and thickness of overlying conglomerate were used to define a critical void diameter and to dimension borehole spacing over the site to locate dangerous caverns.

Mined Openings

Based on the criteria shown in Figures 5.13 and 5.14, limiting depths for hazardous openings subject to extensive roof collapse are summarized below:

a. For a low bulking factor and a minimum angle of break, α , of 15 deg, the height of caving for a 20-ft-wide opening would be 38 ft, for 40 ft width would be 80 ft, and for 60 ft width would be greater than 100 ft below rock surface.

b. Based on height of opening and the criterion of 10 times height of opening for high bulking factor, a height of 10 ft would indicate a minimum depth of 100 ft below rock surface.

Because sinkhole development above mines depends on the competency of the overburden as well as the width, length, and height of the underground opening, no general rule of thumb can be quoted regarding a safe depth. Each case must be considered on its own merit.

Surface subsidence effects depend on the areal extent and existing conditions of mines, type of overburden, and many other factors. Evaluations of subsidence potential above mined areas should include analysis of ability of:

a. The mine roof to span existing openings

b. Existing pillars to support the overlying strata

c. The mine floor to support the existing pillars

EVALUATION OF FOUNDATION SAFETY

Conditions Affecting Structural Foundations

For major structures, a complete geologic profile, showing all solution features, quality and condition of overburden and bedrock, and groundwater conditions, is necessary in evaluating foundation problems and treatment alternatives. All cavities bridged by overburden should be either grouted or excavated and backfilled, depending on the depth of overburden. For shallow overburden where excavation is carried to the bedrock surface, the distribution of solid rock zones, compressibility and erosion resistance of infilling materials, and depth of infilling materials in solution-widened joints require evaluation to determine:

a. Required excavation and type of backfill to replace soft or compressible materials.

b. Choice of foundation type, such as mat, spread footings, piles, or caissons (piers).

c. Requirements for checking conditions exposed by the excavation and verifying soundness of rock below foundation elements after excavation.

For deep overburden, the type and amount of infilling materials in solution features require evaluation to determine whether grouting would be an effective treatment. Deep soft zones between limestone pinnacles and stress concentrations from structure loads on limestone pinnacles could result in large differential settlements for a mat foundation, and the use of piles or caissons founded on solid rock might be a better alternative.

Depman and Backe (1976) describe limestone foundation conditions and preconstruction treatment used for major buildings in Pennsylvania. Foose and Humphreville (1979) describe evaluation of foundation conditions for major buildings and types of foundations in solutioned limestone in Hershey Valley, Pennsylvania. In this case it was possible to shift building locations slightly and minimize problems. Swiger and Estes (1959) and Peck (1960) discuss evaluation of limestone foundation conditions from boring logs for a major steam power plant. In this case, it was possible to design mat foundations supported largely by solid limestone to bridge over softer zones.

In areas of potential hazard, such as abandoned mines in salt deposits and other mineral mines, state geological agencies and the U.S. Geological Survey should be consulted for current information.

Solution of bedrock surface

All solution features in the bedrock surface must be well defined and evaluated to determine the feasibility of treatment to provide a competent foundation. Cavities bridged by overburden, filled solution channels, soft soil zones between limestone pinnacles, and other solution features (Figure 5.1) should be either grouted or excavated and backfilled with concrete or compacted soil, depending on the type of structure and foundation. Extensive surface and subsurface drainage control measures (drainage ditches, subdrains) may be required to prevent infiltration and downward migration of surface water.

Filled sinks

Filled sinkholes (Figure 5.2c) can contain soft compressible sediments and can be subject to renewed erosion and sinkhole development. The latter can occur if unrecognized filled sinks are covered by a reservoir or embankment where increased hydrostatic pressures develop. Unrecognized sinkholes under structures can cause disastrous settlements. Consequently, filled sinks must be located and their areal extent defined. Closed depressions within proposed sites should be investigated by borings, test trenches, or pits to determine the depth and extent of the sink area, type of infilling materials, open joints or fissures, and groundwater variations during dry and wet seasons. Filling materials that will remain under structural foundations must be classified and tested to determine compressibility, consolidation, bearing capacity, and erosion susceptibility. Evaluation of foundation safety (when filled sinks extend below the foundation excavation depth) involves two major considerations: future erosion potential and bearing capacity and settlement. However, for critical or safety-related structures filled sinks should be either avoided or completely excavated and backfilled with competent soil or lean concrete in a manner similar to that shown in Figure 6.1.

Erosion potential. Long-term changes in groundwater levels can reactivate piping of infilling materials into open joints or fissures near the bottom of filled sinks. A significant increase in the groundwater level could initiate erosion of sandy clays (SC), lean clays (CL), and silts (ML). Conversely, a lowered groundwater level followed by high precipitation and surface drainage could cause increased downward percolation and erosion of susceptible infilling materials. In evaluating erosion susceptibility of clays, pinhole tests on undisturbed samples and tests for pore water salts should be used (Sherard, 1976). In situ single packer or double packer water pressure tests or grout tests can also be used to determine susceptibility to erosion and existence of open joints or fissures that may not be readily apparent from examination of test pit or trench excavations. When erosion-susceptible soils in filled sinks, open joints, or fissures are found, complete excavation and backfilling with suitable materials should be specified during foundation excavation.

Bearing capacity and settlement. Infilling materials within sinks extending below the structure foundation level require evaluation of bearing capacity and settlement. Results of shear strength and consolidation tests on undisturbed samples of the weaker materials should be used in evaluating bearing capacity and settlement. Volume VI of the PSAR on the North Coast Nuclear Plant No. 1 gives examples of these types of evaluations. Two important issues should be considered in areas where filled sinks exist above limestone pinnacles:

a. Softer zones usually exist at the contact between residual soils and the tops of pinnacles, and stress concentrations at these locations govern bearing capacity.

b. Where filled sinks or residual soils are excavated to the depth of rock pinnacles, variable areas of soft sediments and limestone may not provide adequate bearing areas on sound rock for footing or mat foundations. Additional excavation and backfilling may be necessary to provide a uniform bearing area.

Cavities below bedrock surface

Cavities below limestone bedrock surface (Figures 5.2a and 5.3) can be covered by various thicknesses of jointed limestone, overlain by residual soil, alluvial soils, or other sedimentary rock. The stratigraphy and engineering properties of the overlying materials, as well as joint patterns and solution defects in the limestone above the cavity, must be defined and evaluated to assess their effect on cavity stability. Erosion susceptibility of overlying materials and groundwater conditions that influence potential sinkhole development must also be considered. Obviously, sites underlain by extensive cavities, interconnected with solution joints, such as shown in Figure 5.3, are preferably avoided.

Potential for enlargement. Natural cavities below bedrock surface can increase in size by dissolution of the carbonate rock, progressive spalling or fall-in of roof rock, or by erosion of infilling materials. Enlargement resulting from the slow dissolution of rock such as limestone or dolomite is not a critical factor. The maximum rate of dissolution of limestone at the North Coast Nuclear Plant No. 1 was conservatively estimated to be 1.5 cm/100 years. Roof spalling and fall-in depends on the strength of the carbonate rock, type and extent of jointing, width of joints or fissures, type and extent of joint filling materials, and in situ stresses. Deformation of strata at intersections of cavities can also initiate enlargement. Figure 5.18a shows an example of enlargement of a cavity by progressive collapse of roof rock. The width of the collapsing sections becomes smaller as they progress upward, so that a stable arch is eventually formed. The process is not quite complete in this example, as the tension crack in the roof shows. Evaluation of the factors controlling roof spalling and fall-in should be based on examination of drillers logs, boring or core hole logs, rock cores, borehole camera or TV surveys, groundwater variations and in situ seepage rates from piezometer observation, results of tests on rock cores and infilling materials, and examination of any accessible cavities in the local area. Considerable experience and judgment is necessary in estimating maximum possible enlargement considering in situ stresses and structure loadings, erosion potential of joint filling materials, and possible groundwater changes.

Effect of infilling materials. Cavities below bedrock surface are often completely or partially filled with soft compressible sediments. Infilling materials may provide partial roof support as shown in Figure 5.18b. Loss of support could occur in cavities above the groundwater table in the event of a future rise in groundwater level, which could cause softening of infilling materials. In cavities below the groundwater table, future lowering of groundwater level could cause drainage and consolidation of infilling materials.

In addition, infilling materials inhibit uniform distribution of grout and require closer spacing of groutholes to fill interconnected cavities and solution channels. The extent and engineering properties of infilling materials should be thoroughly defined and their potential for compression under structure loads evaluated to determine the need for excavation, removal, and replacement with stable material. The feasibility of grouting to provide a stable condition should also be evaluated.

Cavity stability. Cavities within the influence zone of structure loading should be evaluated for stability. Although specific guidance is not available on the minimum size-depth ratio that requires evaluation, cavities as small as 5 ft at depths less than 200 ft should be considered. Stability evaluations require knowledge of the joint pattern, joint strengths, intact rock compressive and tensile strengths, in situ elastic modulus, Poisson's ratio, and K_o (the ratio of horizontal effective stress to vertical effective stress) for the rock mass. If shale or other fine-grained sedimentary rock overlies the cavernous rock and will not be excavated, the contribution of these layers to cavity stability should also be considered. The main objective in evaluating cavity stability is to determine whether roof collapse under imposed structural loads could occur or could progress into overlying overburden soils where seepage erosion could lead to sinkhole development.

Evaluation of cavity stability for complex solution features such as shown in Figures 5.18 and 5.19 would be extremely difficult. Defining the size and shape of the features would require numerous borings and bore hole television or camera surveys and a complex analytical model. Complex solution effects often exist in the upper zone of soluble rock formations. This zone is frequently excavated and treated during foundation excavation, and the main task is safety evaluation of large cavities below excavation rock level, such as the opening shown in Figure 5.19b. Where competent rock surrounds the cavity and long-term sinkhole development is not a problem, a simple deep beam analysis can be made for imposed structure loads (Obert and Duvall, 1967, pages 518-524). An example of such an analysis is shown in Figure 5.20. However, this condition would be the exception since limestone and other sedimentary rocks are usually jointed. Close spacing of vertical joints, as compared to cavity dimensions, could produce the condition shown in Figure 5.21. The usual result of jointing is to greatly reduce the factor of safety against failure. However, high horizontal ground stress (e.g., $\sigma_h = 2\sigma_v$) increases the shear resistance along vertical joints and a higher factor of safety would apply. On the other hand, buckling of roof beams can

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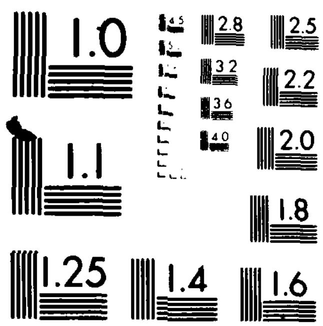

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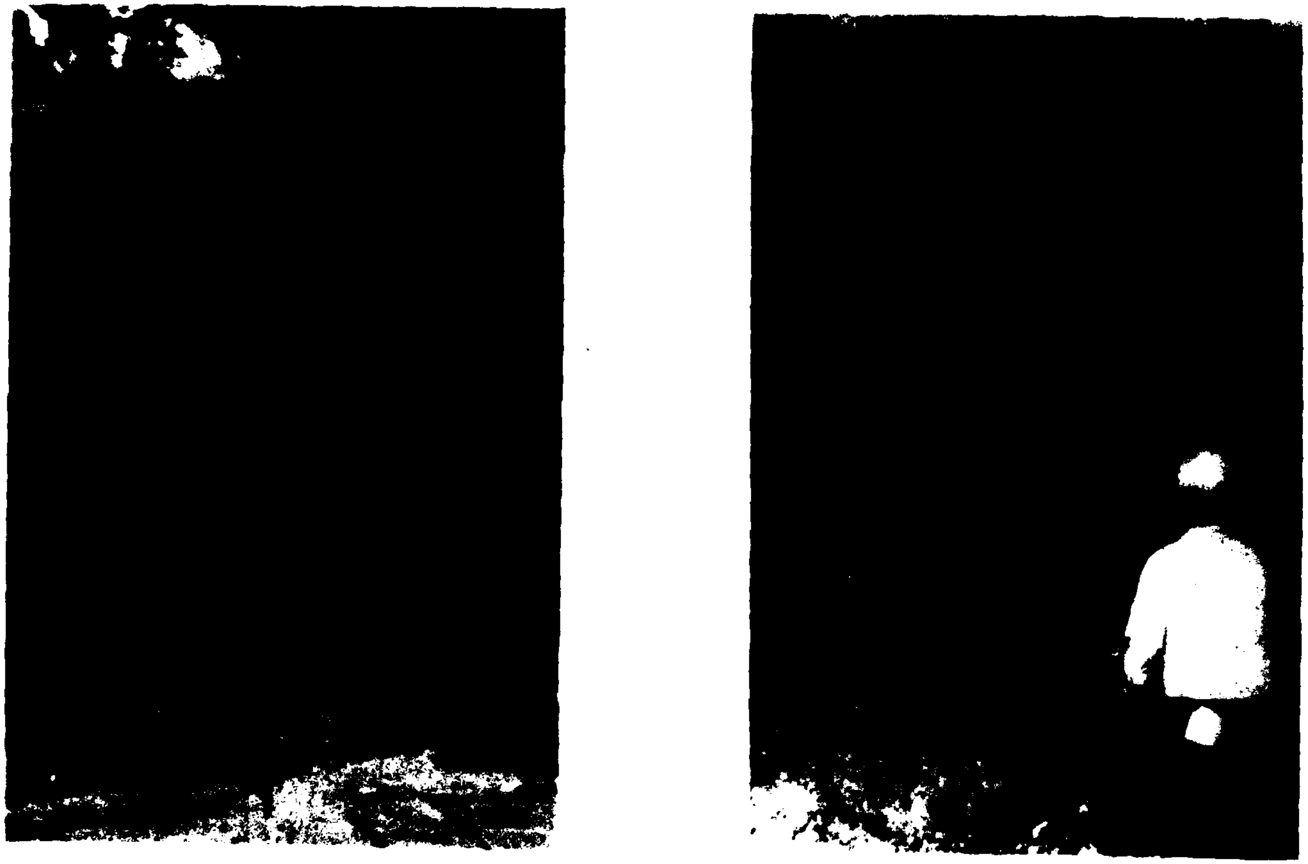


a. Development of a stable arch

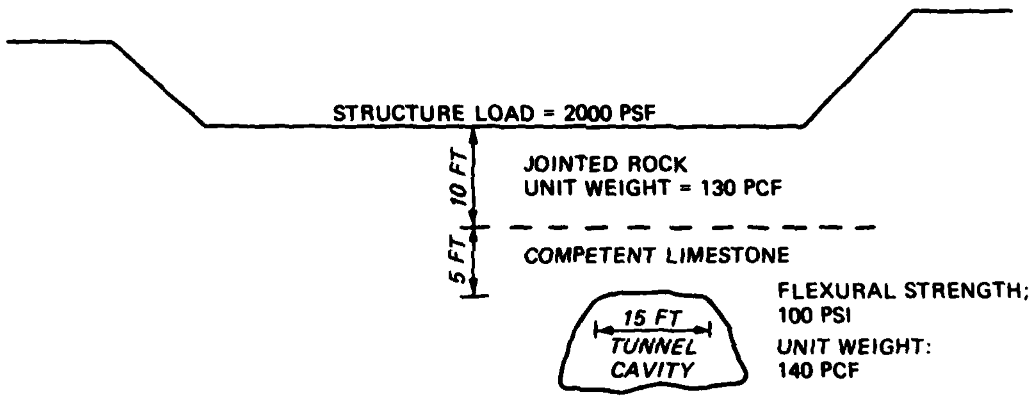
b. Weathering of infilling material

Figure 5.18. Cavities partially supported by infilling material, Hartsville Nuclear Plant

a. Solution-widened joints

b. Solution-widened joints and cavity

Figure 5.19. Examples of complex solution features, Hartsville Nuclear Plant



VERTICAL PRESSURE AT TOP OF COMPETENT ROCK

2000 PCF + 10 FT X 130 PCF = 3300 PCF = p

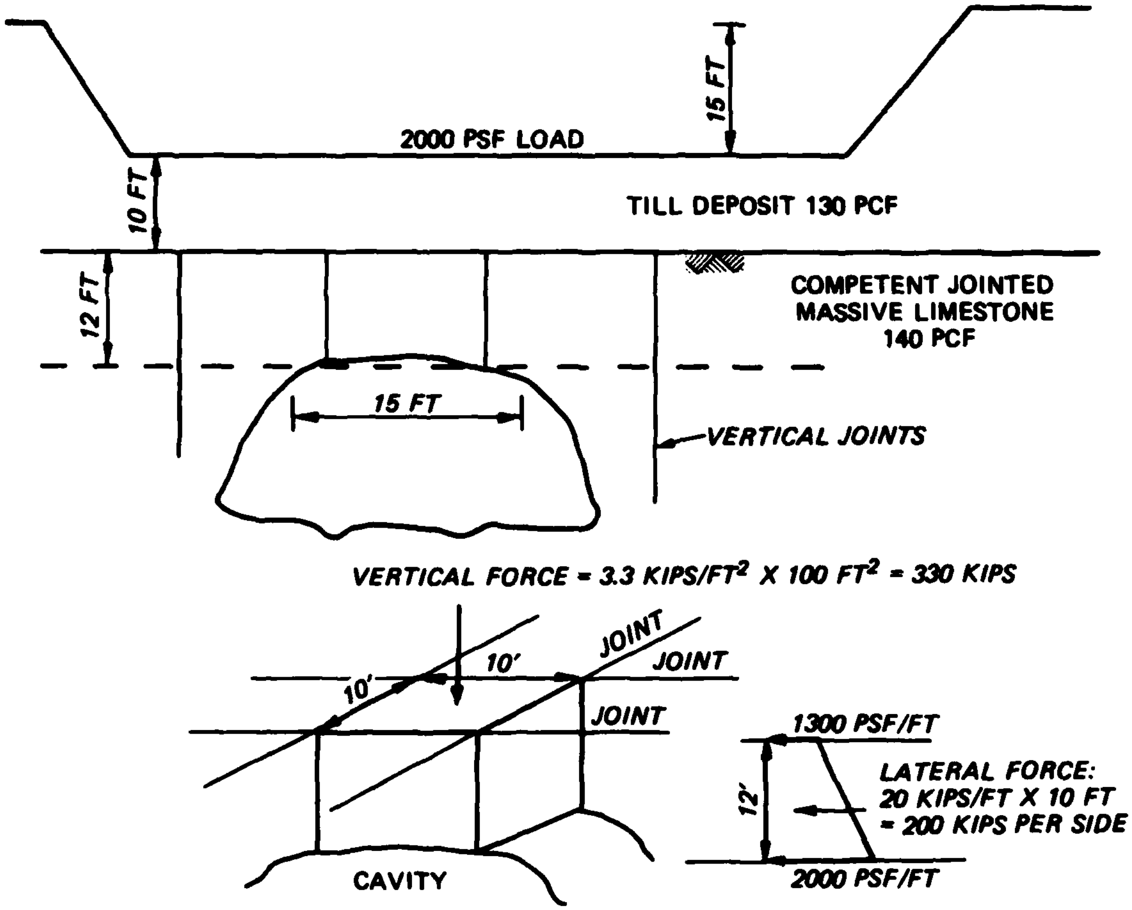
FLEXURAL STRENGTH COMPETENT LIMESTONE
= 100 PSI X 144 = 14400 PSF = R_0

FACTOR OF SAFETY AGAINST FLEXURAL FAILURE:

$$F_s = \frac{2R_0 t}{(\gamma + P/t)L} = \frac{2(14400)5}{\left(140 + \frac{3300}{5}\right)15}$$

$$F_s = \frac{144000}{12000} = 12$$

Figure 5.20. Stability analysis of cavity for a simple case



JOINT SHEAR STRENGTH:
COHESION = 0
FRICTION, θ = 40 DEG

FACTOR OF SAFETY AGAINST VERTICAL SHEAR:

SHEAR RESISTANCE EACH SIDE = 200 KIPS (TAN 40°)
= 170 KIPS

4 SIDES X 170 KIPS = 670 KIPS

$$F.S. = \frac{\text{SHEAR RESISTANCE}}{\text{VERTICAL FORCE}} = \frac{670}{330} = 2$$

Figure 5.21. Effect of joints on cavity roof stability

be an important failure mechanism in rock with high lateral stresses. For more complex jointing, bedding, and cavity configuration, computer modeling for jointed rock masses using discrete elements can be used if a two-dimensional model can be adequately defined (Maini, et al., 1978). Use of finite element models that assume a homogeneous, elastic continuum may not adequately represent joint failure modes. However, for cavities at depths of 50 ft or more, finite element analyses could serve to define the general stress field. Discrete element analyses simulating the jointed rock could be used to study the local area around each cavity. Factors of safety against failure should generally be greater than 2.

Mined openings. The possible existence of mined openings beneath a site can be assessed from a thorough review of all available geologic and historical information for the region. Once it is determined that the area has been undermined, surface and subsurface investigations should be made to determine the following:

a. Depth and extent of mining.

b. Size of existing mined openings.

c. Extent and amount of surface subsidence.

d. In situ conditions of mine walls, roofs, floors, and support columns.

e. Amount of roof collapse and distress in overlying strata.

Where entry is not possible, the size of openings and in situ conditions can be evaluated from borings, drillers logs, inspection of cores, and borehole camera or TV surveys. If it is not possible to define the complete geometry of the mine, a rational evaluation of stability under structural loading may not be possible. In this case, the conservative approach of planning remedial stabilization (grouting, or otherwise filling voids under the site) may be necessary. Stabilization measures are summarized in Chapter 6.

Potential evaluation of subsidence and collapse for proposed sites over mines should include:

a. Potential for subsidence or sinkhole development from roof fall.

b. Potential subsidence from pillar bearing failure.

c. Potential subsidence from pillar collapse.

Mabry (1973) describes evaluation of factors b and c above for an acid mine drainage treatment plant in Pennsylvania. After a study of visible ground surface conditions, all available documentation (mine maps, boring logs, cross sections, etc.), definition of the problem, and subsurface explorations, an estimate was made of pillar stability. Finite element analyses were then used to determine possible ground surface subsidence from likely zones of mine collapse in areas of weak pillars. The resulting maximum surface distortions for different degrees of mine collapse conditions were evaluated for their effect on proposed structures.

Conditions Affecting Water Retention Structures

Ponds and reservoirs for water storage are vulnerable to sinkholes and seepage under the embankments. A complete picture of bedrock solution conditions, depth of overburden, and type of overburden materials, including compressibility and erosion susceptibility, is necessary for the entire site. This information is required both for evaluating potential erosion and sinkhole problems in selecting the best reservoir area and for deciding on the best treatment to prevent leakage, piping into open fissures, and sinkholes. Extensive excavation, bedrock surface treatment, and/or a seepage cutoff wall or trench may be required under reservoirs or water retention embankments. For example, Soderberg (1979) describes unexpectedly extensive solution-related conditions occurring under an embankment in karstic terrain in the Tennessee Valley.

The existence of cavities below reservoirs or embankments would require evaluation for stability under imposed loading and for potential seepage-induced erosion (piping) in overlying soils. Even where cavities are stable, if soil-filled solution joints or open joints connect the cavity with overburden soils, the possibility of piping and sinkhole development in the reservoir area would be a danger. Seepage through interconnected stable cavities beneath an embankment could cause erosion of foundation soils and collapse of the embankment. Fetzer (1979) and Holland and Turner (1980) describe remedial treatment, including a positive cutoff wall, used at Wolf Creek Dam, Kentucky, which was threatened by piping and leakage through solution cavities (Figure 5.3).

Embankment foundations

The primary danger to embankments for spray ponds, holding ponds, and similar types of reservoirs on karst terrain is from underseepage, piping, and erosion of soil materials contained in filled sinks or in interconnected solution features. Also, nonuniform settlement of the embankment could lead to transverse cracking and eventual piping through the embankment. Permeable soils overlying weathered bedrock require a positive cutoff beneath the embankment and an impervious lining of the reservoir surface area. Even then, filled sinks, solution joints, and cavities below bedrock should be identified and treated (Chapter 6). These conditions would be especially dangerous in areas where rock strata and groundwater tables dip away from the reservoir area. Figure 5.22 shows logs of borings at 100-ft spacing and indicates solution and seepage features, 18 to 20 ft below overburden soils, which would be dangerous to water retention structures without remedial measures. Closely spaced vertical and angle borings (20 to 40 ft) should be made along proposed embankment locations to define the maximum depth of hazardous underseepage. In some cases, grouting may provide an adequate control of seepage in cavities. Additional pumping tests and a test grouting program should be undertaken to determine the suitability of this treatment method. Otherwise, an expensive deep concrete cutoff wall might be necessary if a better site were not available. Groundwater studies and pumping and grout take tests are described in Volume 7 of the PSAR for the North Coast Nuclear Power Plant No. 1, Puerto Rico.

Reservoir safety

Reservoirs for emergency cooling water and other critical water supplies that incorporate natural ridges or hills as parts of water

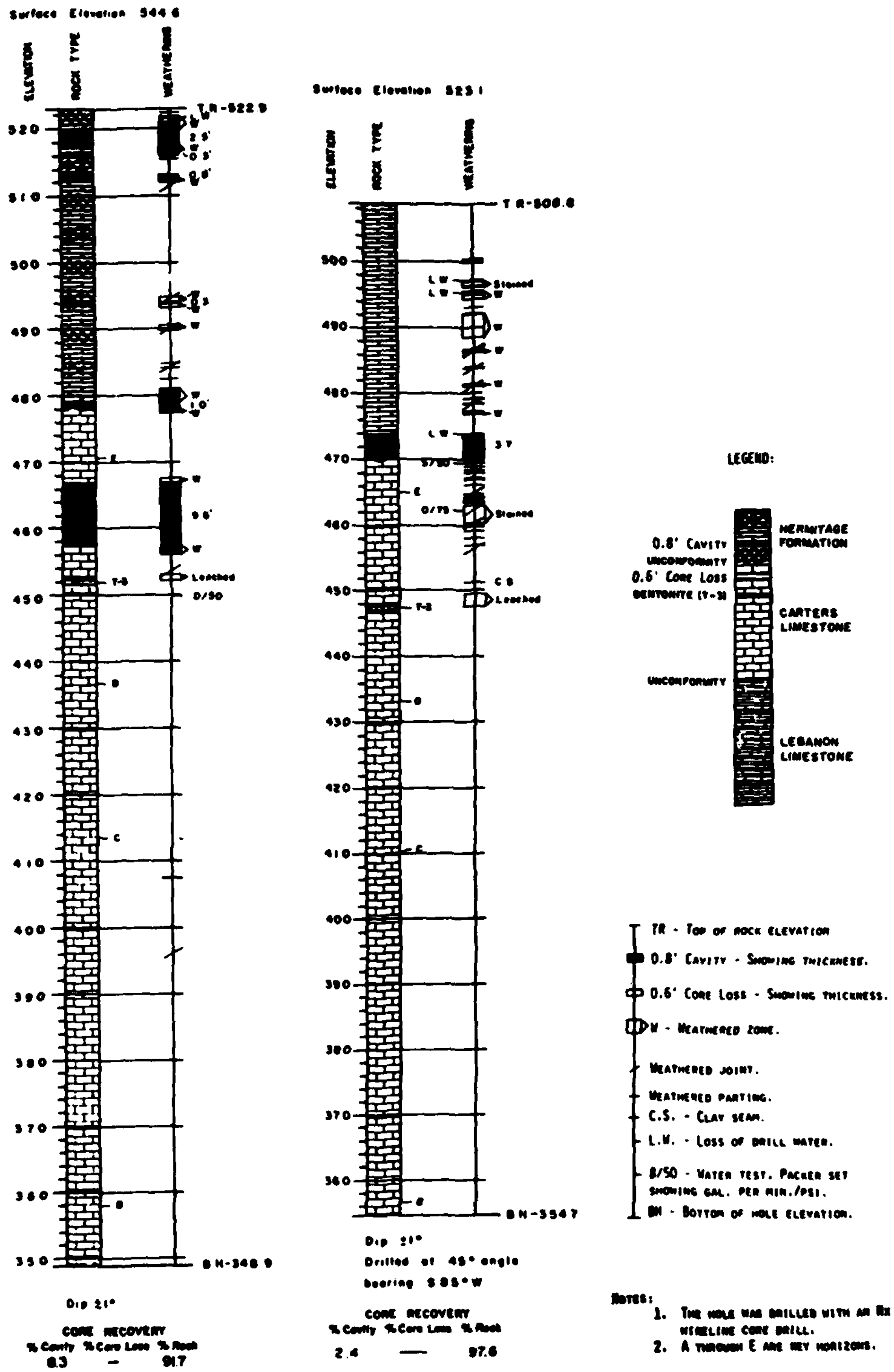


Figure 5.22. Boring logs showing cavities at Hartsville Nuclear Plant site (Tennessee Valley Authority, 1975)

retention embankments require special groundwater studies. These studies should determine the gradients and direction of natural groundwater seepage from observations of piezometers placed in overburden soils and each water-bearing formation to the maximum depths of possible solution features. If the results indicate that natural seepage flows away from the proposed reservoir beneath a flanking ridge, potential leakage could occur from the reservoir by cracking of the clay liner (from differential settlement) and downward seepage through erodible subsoils into interconnected solution joints in the underlying bedrock. This process could result in the development of sinkholes and sudden reservoir drainage several years after construction.

Where adverse subsurface seepage and solution features are a potential danger, the consolidation and erosion characteristics of overburden soils in the reservoir area should be thoroughly investigated. Compressible and erodible soils such as silts, clayey silts and clayey fine sands should be removed and replaced with compacted impervious clay soil. Particularly dangerous are soils or rocks containing highly soluble minerals such as halite, gypsum, or anhydrite (James and Lupton, 1978). Where overburden soils are less than 10 to 15 ft thick, test trenches should be made to investigate bedrock surface conditions, especially at locations where bedrock weathering is apparent. Abutments of dams should be considered, as well as foundations and reservoir areas. Any filled sinks within the reservoir area must be found and must receive special grouting and/or backfill treatment.

Reservoirs over mines

Water storage reservoirs over even deep mines can be subjected to sinkhole development or loss of water through cracks and fissures produced by mine collapse. Consequently, borings and pressure tests that indicate open joints in sedimentary formations above mines should preclude the siting of reservoirs in such locations. Areas within or near the edge of subsidence zones should also be avoided. A pertinent reference on mining under reservoirs is Babcock and Hooker (1977).

CHAPTER VI: FOUNDATION TREATMENT AND MONITORING

TREATMENT METHODS

Considerable experience exists in the treatment of solution features and mined openings to improve stability, decrease water losses by seepage, and prevent sinkhole development. The critical part of any treatment method is verifying the success of the treatment and monitoring future conditions to detect problems in time to correct them before they become serious. Treatment methods, verification criteria, monitoring techniques, and provisions for remedial measures after construction are summarized in this chapter.

Filled Sinks and Solution-Widened Joints

Treatment of filled sinks and solution-widened joints includes excavation and backfilling, grouting, preloading of filled joints (to increase bearing capacity and reduce settlement), and provisions for seepage control.

Foundation areas

In foundation areas, filled sinks and solution-widened joints extending below the excavated foundation level in rock are usually excavated and backfilled with concrete to a minimum depth of 2 times the maximum width of the joint, as shown in Figure 6.1. However, for filled sinks that lead to deeper solution joints subject to seepage erosion of infilling materials, the following treatment may be necessary:

a. Complete excavation of the sink.

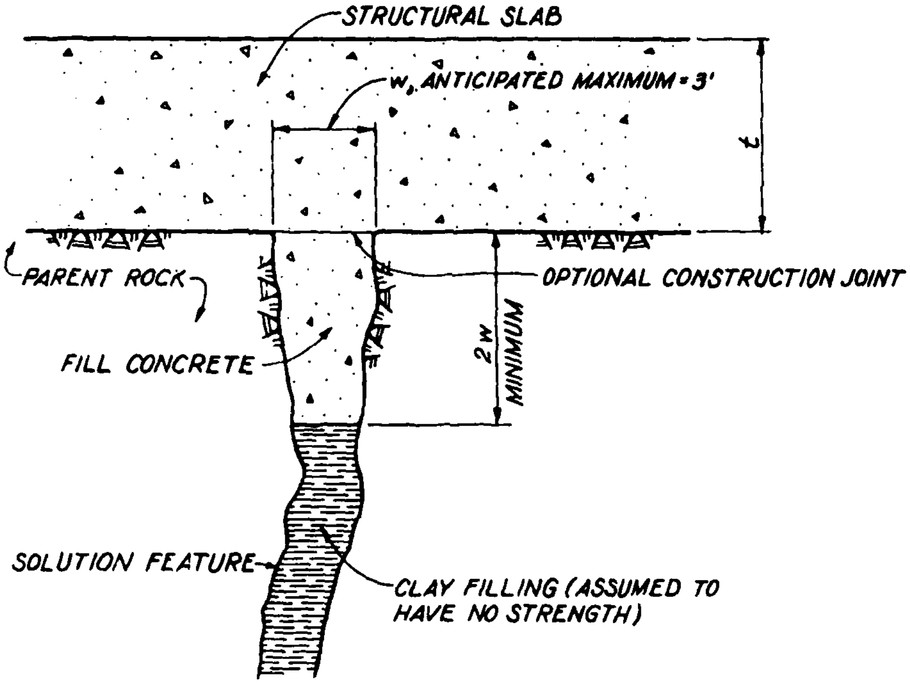
b. Plugging the bottom of the sink with concrete.

c. Backfilling with concrete.

d. Compaction grouting around the base of the sink.

Reservoir areas

In reservoir areas, vertical seepage through residual soils and rejuvenation of a sinkhole is a critical danger. Consequently, extensive



BUILDING	SLAB THICKNESS	MAX. SLAB SPAN
REACTOR	12' ±	65'
FUEL	6' ±	60'
AUXILIARY	6' ±	60'
RADWASTE	4' ±	40'

NOTES:

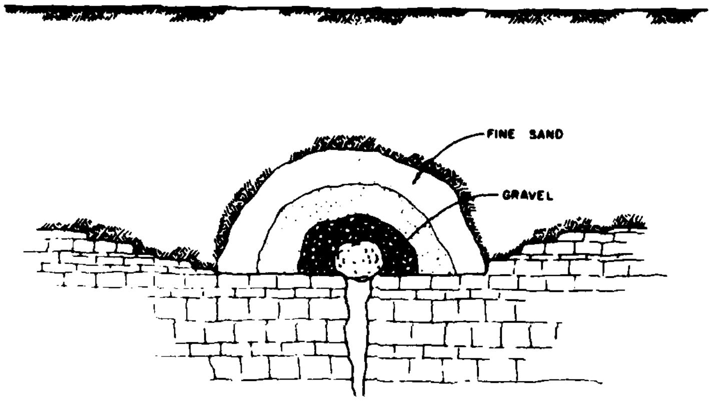
1. CLEAN ALL SOLUTION FEATURES TO A MINIMUM DEPTH OF 2w. IF FEATURE WIDENS WITH DEPTH, CLEAN TO A DEPTH WHERE WEDGING CAN BE ACHIEVED. FINAL DEPTH OF CLEANING FOR ALL FEATURES TO BE COORDINATED WITH PROJECT GEOLOGIST.
2. DEGREE OF CLEANING TO BE THE SAME AS FOR HORIZONTAL FOUNDATION SURFACES.
3. IN THE EVENT THAT A ZONE OF NUMEROUS CLOSELY SPACED SOLUTION FEATURES IS FOUND (NO INDICATION OF THIS FROM DRILLING), w SHOULD BE TAKEN AS THE ZONE WIDTH.
4. FEATURES LESS THAN 3" WIDE CAN BE DISREGARDED EXCEPT FOR NORMAL FOUNDATION CLEANUP.

Figure 6.1. Criteria for treatment of solution-widened joints used by TVA at Hartsville Nuclear Plant site (Tennessee Valley Authority, 1975)

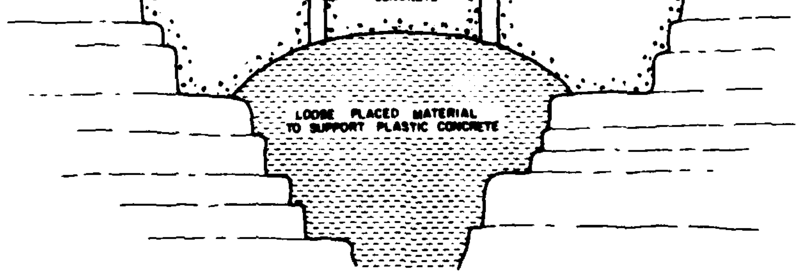
grouting at the contact between overburden soils and bedrock in addition to grouting of the rock below embankments may be a necessary treatment. Grant and Schmidt (1958) describe extensive and successful grouting of solution channels and the overburden soil-bedrock contact for a large (475 ft by 550 ft) elliptical log pond for a paper mill at Calhoun, Tennessee. The extensive grouting was necessary to stop sinkhole development and leakage. The pond was underlain by 40 ft to 60 ft of alluvial and residual soils overlying inclined beds of limestone and dolomite. Where critical or safety-related reservoirs are involved, grouting should be regarded primarily as a measure for controlling water loss, as it cannot provide a positive defense against eventual piping or erosion of joint-filling materials. Positive protection of the reservoir area may require complete stripping of overburden soils and treatment of the bedrock surface. Wide and deep solution joints in bedrock below embankments may also require special treatment. A positive cutoff using large diameter drilled holes backfilled with concrete and grouting, as described by Soderberg (1979), Fetzer (1979), or Holland and Turner (1980), may be necessary in extreme cases.

Seepage control in other areas

Filled sinks or solution-widened joints at bedrock surface that drain subsurface water into deeper solution channels, even though outside structure or reservoir areas, may require special seepage control. If such filled sinks or solution-widened joints were grouted and subsurface drainage impeded, other sinks could develop and endanger nearby structures. If untreated, these sinks could be reactivated by changes in groundwater levels or by increased surface drainage from site grading. Consequently, seepage control measures such as shown in Figure 6.2 may be necessary to control subsurface seepage and prevent erosion. The necessary alternative would be that all subsurface water is prevented from entering the site and all surface water is carried offsite in storm drains and paved ditches.



a. TYPICAL SECTION THRU TREATED SINKHOLE



b. TYPICAL SECTION THROUGH STRUCTURAL CONCRETE DOME

Figure 6.2. Treatment of solution sinkholes to control seepage (Reitz and Eskridge, 1977)

Solution Cavities

Solution cavities below bedrock surface that are intercepted by the foundation excavation are normally excavated, cleaned, and backfilled with concrete. Solution cavities being cleaned prior to concrete backfilling at Hartsville Nuclear Power Station, Tennessee, are shown in Figures 5.19 and 6.3. Cavities in bedrock below foundation levels should be grouted to fill existing voids and open joints. Criteria and guidance on grout mixes, pressures, and grouting procedures are contained in Technical Manual 5-818-6 (U.S. Army, 1981), and in the Grouting Manual of the Water Resources Commission of New South Wales, Australia (1977). Core borings and water pressure tests are usually necessary to verify adequacy of the grouting program.

Mined Openings

Treatment of mined openings includes selective support and filling methods using grout and other materials. Gray, et al., (1974) summarize the current state of the art.

Support methods

Selective support methods are summarized in Table 6-1, based on Gray, et al., (1974). A diagram illustrating the grout column method is shown in Figure 6.4. Gray, et al., (1976) describe a case history of subsurface stabilization techniques, including drilled piers and piling used for structure support and grout columns and dry fly ash injection for support of roadways. Mansur and Skouby (1970) describe the use of grouting to control settlement of a power company sales building in Belleville, Illinois. High-slump concrete grout, placed through 6-in. drill holes, was used to fill mine voids after first constructing a concrete grout wall around the area to be filled. The geotechnical investigation and use of borehole photography to define the mine openings are described. Data on grout mixes and verification drilling results are also presented.

Figure 6.3. Solution cavities prior to concrete backfilling at Hartsville Nuclear Plant site

Table 6-1

Summary of Selective Support Methods
(after Gray, et al., 1974)

Method	Conditions for Use	Approximate Cost Range
Grout columns (Figure 6.4) or piers of gravel or crushed stone placed through drilled holes	Mine depth usually between 30 and 150 ft; void height 6 ft or less preferred; overburden not extensively caved; surface accessible.	Approximate cost (1) approximately $1,000 per support. Maximum cost about $2,500 per support.
Piers constructed within the mine	Accessible mine voids, unflooded or drainable, uncaved and safe to enter.	Costs vary greatly depending upon conditions. Typical up-to-date costs unavailable.
Deep foundations; drilled piers or pile foundations	Mine depth less than 100 ft; structure to be supported preferably not yet constructed; surface accessible.	$35 (2) to $50 (3) per lineal foot per support.
Groutcase, drilled piers, cased from mine floors to several feet into mine roof backfilled with concrete and grout	Mine depth usually between 30 and 150 ft; void height 6 ft more more; overburden not extensively caved; surface accessible.	$440 (4) per support.

(1) 1973 costs.

(2) 1972 cost for piles.

(3) 1970 cost for drilled piers.

(4) 1968 cost for only reported case.

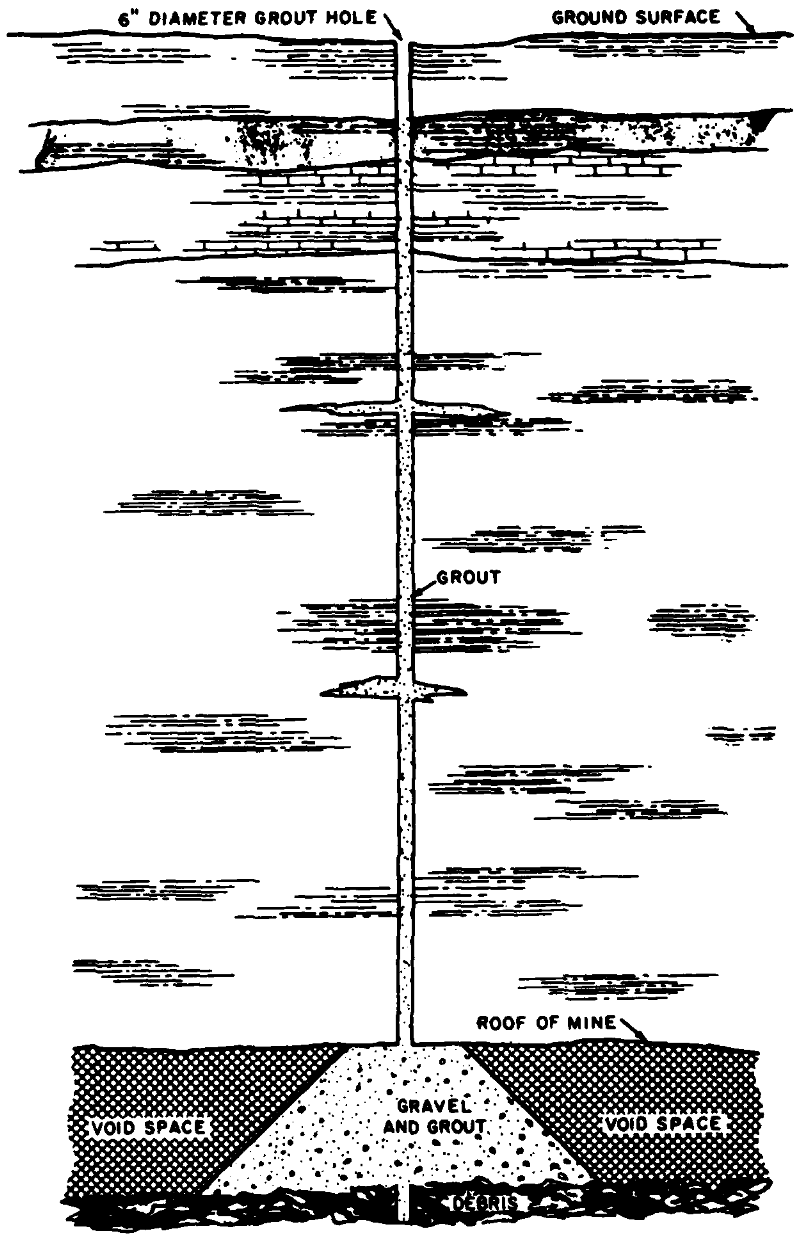


Figure 6.4. Grout column (Gray, et al., 1974)

Filling methods

Filling methods are summarized in Table 6-2 (Gray, et al., 1974). An idealized example of controlled flushing is shown in Figure 6.5. In hydraulic flushing, mine voids are backfilled with granular materials deposited in a water slurry. The main concern is to ensure adequate drainage for consolidation of materials. Supplemental grouting may be necessary to fill voids between mine roof and backfilling materials, especially for remote flushing. The Dowell process is a blind flushing technique using high velocity and continuous flow of water and solids (1 part sand or other solids to 4 or 5 parts water) through an injection hole. The ultimate density depends on the gradation of the solids. Testing after placement would be necessary to determine the need for supplemental compaction grouting to obtain desired support and to fill remaining voids. Pneumatic filling uses air pressure to deposit materials and has found limited use in abandoned coal mine voids. Fly ash injection has been used in remote filling of mine voids. Both pneumatic and hydraulic distribution techniques are used, though case studies of hydraulic and pneumatic backfilling are limited. The Bureau of Mines has continued research to improve the support capabilities and strength of hydraulic sandfill.

Improvement of Seismic Stability

From review of damage to tunnels caused by earthquakes, Dowding and Rozen (1978) indicate that unlined tunnels generally did not experience block falls until the peak surface accelerations exceeded 0.2 g and velocities exceeded 20 cm/sec. Barton (1979) and Barton and Hansteen (1979) showed, from dynamic model tests, that for steeply dipping joints, block falls occurred progressively in the wall between adjacent tunnel openings. By comparison, with gently dipping joints there were no block falls, but only a general settlement. The seismic stability of tunnels, and thus caverns and mine openings, does not appear to be a major problem.

Table 6-2

Summary of Filling Methods for Void Elimination
(after Gray, et al., 1974)

Method	Conditions for Use	Approximate Cost Range
Hydraulic Flushing Controlled	Accessible mine voids; unflooded or drainable; uncaved and safe to enter.	$1.75 per cubic yard of void filled (1)
Remote	Overburden not extensively caved; surface accessible.	$3.00 to $4.00 per cubic yard of void filled (2)
Dowell Process	Overburden not extensively caved; large quantities of water available; mine voids capable of accepting large quantities of water.	$3.00 to $6.00 per cubic yard of void filled (3)
Pneumatic Filling Controlled	Accessible mine voids; unflooded or drainable; uncaved and safe to enter.	$1.50 to $3.00 per cubic yard of void filled in active mines. Cost not determined for abandoned mines.(4)
Fly Ash Injection	Surface accessible.	$4.00 to $24.00 per cubic yard of void filled (5)
Grouting	Surface accessible.	$20.00 to $70.00 per cubic yard of void filled (6)
Overexcavation and Backfilling	Mine voids at shallow depth; no surface restrictions; unflooded or drainable voids.	$1.50 to $7.00 per cubic yard of overburden (7)

(1) 1966 costs.
(2) 1967-1968 costs.
(3) 1973 cost and cost estimate.
(4) 1974 estimated cost.
(5) 1973 costs.
(6) 1973 costs.
(7) 1972 costs.

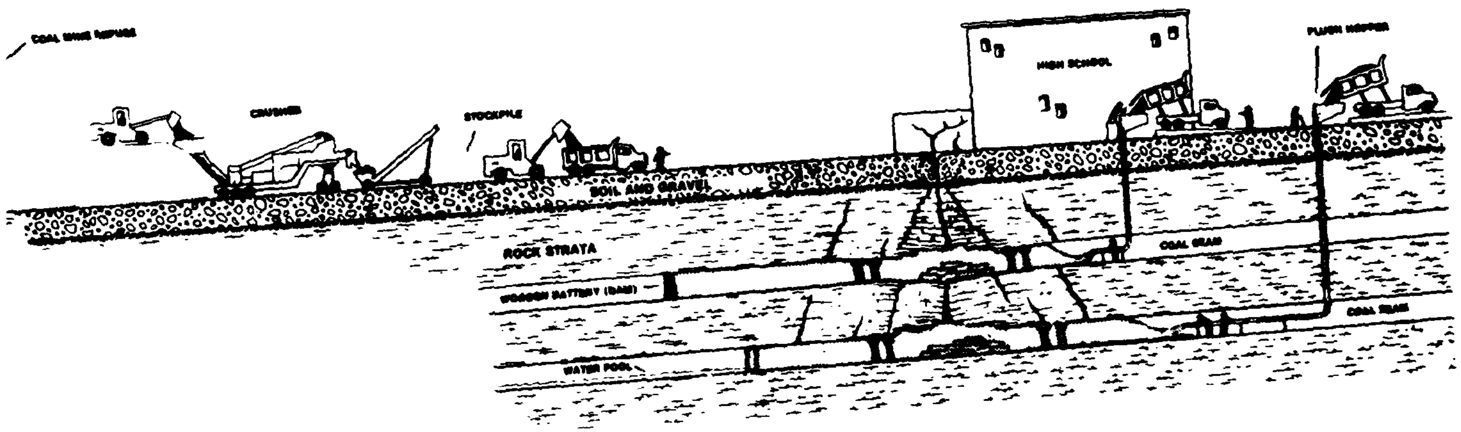


Figure 6.5. Controlled flushing project (Gray, et al, 1974)

However, treatment of loose rock in seismic zones is warranted. Peck (1976) suggests that "solution cavities in limestone, if left open, could permit blocks of rock overlying the cavities to become loosened during an earthquake and conceivably could initiate stoping that could deprive a part of the plant of its support. Filling the cavities with grout, although adding little or nothing to the strength and rigidity of the rock mass, can prevent the initial movements leading to stoping." The same reasoning applies to mines where jointed roof rock could be dislodged during an earthquake.

Potential Problems from Grouting and Filling

Under some unfavorable combinations of site conditions, remedial actions can have results contrary to those intended, or may be the source of other problems. Consequently, particular care is needed to assure that the groundwater regime is sufficiently well defined during site investigations to assure that the consequences of the remedial measures can be predicted. Filling and grouting of subsurface voids may have severe consequences for subsurface water transmission in karst areas. Blockage of flow paths may result in increased flow in adjacent areas, with erosion of soil from solution channels and immediate support problems; or blockage may cause ponding of water upstream, flooding the facility or causing bypass routes to develop in the subsurface, weakening previously stable areas. Under some conditions, cutoff walls or grout curtains, coupled with diversion of all surface runoff from the site, could result in lowering the water table under the site, which could in turn increase instability by removing buoyant support of ceilings over water-filled voids or drying and shrinking of fills. Any errors that produce groundwater contamination in karst terrains may be much more serious than in normal areas, because water transmission is by conduit flow. This results in the rapid movement of any contaminated water away from the site and the absence of decontamination through filtration.

MONITORING

Groundwater Levels

Monitoring groundwater levels after foundation treatment and during the life of the plant is important in determining changes that could endanger foundation safety. As discussed above, the foundation treatment could cause changes in the groundwater regime that might endanger nearby facilities, or such changes could occur through natural causes. A small-diameter perforated plastic standpipe placed in a boring, with the annular space backfilled with pervious sand, can serve as an inexpensive but effective piezometer to monitor general groundwater levels in overburden soils. Piezometers should be installed in underlying rock around critical or safety-related structures and in the foundations of reservoir embankments to monitor water levels that could be different from those in the overburden. Readings should be taken at one- to three-month intervals and especially after heavy rains. Combining water level readings and rainfall data on the same plot can be extremely helpful in defining subsurface seepage patterns across the plant site and the influence of rainfall on changes in groundwater levels.

Surface Drainage

Monitoring of surface drainage during the life of the plant is important in determining that surface water is not escaping into the overburden soils or exposed soluble rocks. Surface ditches and drop inlets to storm drains should be inspected after heavy rains to detect eroded areas. Outlets from storm drainage lines should be checked for erosion. During heavy rains the outlets should be checked to see if they are producing the quantity of water estimated to be entering the system. Low flows could be a clue that open joints are losing water into subsurface soils and remote inspections of storm drain lines could be warranted. Natural outlets such as springs and openings where karst groundwater exits into streams or lakes should also be gaged and checked to determine flows after heavy rains and detect the presence of muddy water. These conditions could indicate erosion of soil-filled solution features.

Settlement

Settlement observations during the life of the plant may be warranted to detect signs of subsidence in areas of filled sinks and underground mines. Regional settlement observations are especially important in mining areas to detect surface subsidence zones encroaching into the plant site. It may be possible to obtain observation data on permanent bench marks in the region from appropriate agencies. On the plant site, settlement observations may be warranted using reference points imbedded slightly above the top of grouted cavities or the treated openings of filled sinks. Future caving at these locations would be noted immediately by a drop in the settlement rod attached to the reference point. These observations would be especially important at accessible locations within critical structures and adjacent to buried water intake conduits. All settlement observations should be referred to bench marks in known stable locations.

PROVISIONS FOR FUTURE REMEDIAL TREATMENT

Foundation Access

Access to foundations beneath major structures for supplemental foundation grouting should be provided. Capped access pipes through concrete mat foundations, directed toward solution features grouted during foundation construction, would be valuable in the event remedial grouting were required during the life of the plant.

Records

Complete construction records should include all locations and treatment data for solution features. These records would be invaluable in determining possible causes of distress and in planning remedial treatment.

CHAPTER VII: CONCLUSIONS

In the preceding pages, a survey is offered of important considerations in the siting and geotechnical engineering of nuclear power facilities in locations that have a potential for the occurrence of underground openings, of either natural or artificial origin, that could lead to ground collapse. Also considered are related ground conditions such as sinkholes and open joints that offer other kinds of hazards, such as piping, seepage, and the threat of loss of integrity of water reservoirs. The conceptual framework for this survey has as primary elements the four questions:

a. Prediction. In what areas or under what geological or environmental conditions should problems of ground collapse be anticipated?

b. Detection. By what methods can underground openings and related features be detected and delineated?

c. Evaluation. Are the conditions encountered safe or unsafe?

d. Treatment. What engineering procedures can be used to remedy unsatisfactory conditions?

The purpose of this survey is to provide guidance, for those involved in the siting of nuclear facilities, on geotechnical engineering questions raised by the potential occurrence of underground openings, available methods for dealing with the problems involved, and sources of additional information. A treatment in depth of all the topics covered is not attempted, but sources of additional information are identified by reference to the open literature.

PREDICTION

Roughly one third of the area of the continental United States is underlain by rocks that may be subject to ground collapse as a result of solution processes, pseudokarst conditions, or mining activity. Major areas of such conditions are well identified and mapped, but a potential also exists for the occurrence of cavity-related hazards in other areas. Assurance of the safety of a project against such hazards demands a thorough study and understanding of the regional and local geology and environmental conditions that may be contributory factors. It also requires the recognition of geological or environmental warning signals, and when they occur, a conscious, explicit evaluation of their significance.

The critical elements of the geological site investigation include the stratigraphic sequence, rock and rock mass properties, the nature and evolution of the hydrologic regime, and the geomorphic history of the site. Usually cavern development is initially controlled by rock mass properties such as the structure, extent, and orientation of discontinuities, the stratigraphy, and mass permeability. These properties also affect the stability. On the other hand, rock properties such as lithology, porosity, and rock permeability may be subordinate in importance. The development of rock and rock mass data must be integrated with and complemented by a conceptual understanding of the geomorphic and hydrologic evolution of the area. The critical elements of hydrologic and geomorphic data include base level changes, evolution of stream valleys, the presence or absence of confined aquifers, and recognition of ancient land surfaces that may have been subjected to such processes or conditions. Also required is a review of mining activity, including the presence of coal or ore bodies, underground mining, and solution mining.

DETECTION

Although site investigations in karst regions are often complicated undertakings, it is possible to plan programs using existing knowledge of the local geology and complementary surface, remote sensing, geophysical, drilling, excavation, and subsurface exploration methods that can adequately define subsurface conditions. Standard site investigation methodologies must be adapted to address the possible site complexity produced by subsurface cavity systems. Geophysical methods and programs that work well in delineating stratigraphy and simple geologic structure in routine site investigations are often found to be of little value in finding and delineating cavities.

In planning, conducting, and interpreting the results of a site investigation in a karst environment, the investigator should remember that (a) foundation conditions for critical structures ultimately must be verified by drilling or excavation and (b) it may never be practical or even possible to detect and delineate every solution feature at a site. Consequently, a decision must be made in such cases as to the largest undiscovered cavity that would be tolerable, on the basis of the effects of such cavities on the performance of important structures. Spacings or measurement intervals for geophysical exploration programs should be selected to be consistent with such cavity sizes, and finally, verification by drilling will be required with borehole spacings established in the same way. In some cases, depending on the design and function of structures involved, an exploratory approach that emphasizes zonation, rather than identifying discrete cavities, may be most appropriate.

Where water retention structures are involved, even quite small cavities may have major detrimental effects on performance. Reliance may have to be placed on engineering measures that reduce the need for complete definition of subsurface conditions, such as the construction of a positive cutoff wall.

From a review of probabilistic techniques for optimizing the allocation of exploration effort to detect cavities, the following comments can be made:

a. No comprehensive, sophisticated, practical probabilistic procedure exists at this time to describe the detection problem. The present probabilistic techniques are severely limited by inaccurate assumptions, and they should be used for general guidance only. However, research in this field is very active, and improvements in probabilistic methods for the d·'ign of search programs are to be expected in the near term.

b. The process of cavity detection is largely subjective in nature and the purpose of probabilistic techniques is primarily to prevent mistakes in logic.

c. Most search theory techniques, such as Koopman theory, sequential and multiple-stage search, and linear programming methods in general, yield results that agree with common sense conclusions.

EVALUATION AND TREATMENT

The greatest dangers to foundation safety in karst terrain are from filled solution features at the bedrock surface and filled or open cavities at shallow (relative to cavity size) depths below bedrock. The compressibility and erosion potential of infilling materials in solution channels and cavities must be adequately evaluated to determine bearing capacity, settlement, and susceptibility to future erosion caused by possible changes in the groundwater regime. Where these features exist under shallow overburden in areas of safety-related structures and service reservoirs, they should be excavated and filled with concrete in structure areas or with either concrete or well compacted impervious clay in reservoir areas. Where deep and impervious overburden exists, multiple stage consolidation grouting may be adequate if properly done and based on test grouting programs.

The stability of natural cavities below bedrock surface to depths of at least 200 ft should be considered. The size of cavity, depth, joint patterns, joint conditions, type of rock, and bedding above the cavity are primary factors that influence roof stability and the depth of consideration . Increases in vertical stresses from structure loads, resulting in a decrease in the ratio of lateral to vertical stresses, can cause tensile stresses in the cavity roof and lead to instability. Sites underlain by complex colution cavity systems should be avoided since a realistic evaluation would be extremely difficult. In other areas where jointing and cavity geometry can be well defined, analytical procedures such as the distinct element technique developed for modeling jointed rock masses may be appropriate for evaluating stability.

In areas underlain by coal mines, sinkhole development and surface subsidence can occur many years after mining has stopped. Sinkholes can occur from mines as deep as 150 ft and significant subsidence effects occur from active mining at depths of several thousand feet. Failure of pillars or the mine floor in abandoned mines can result in surface subsidence regardless of depth. Consequently, any mined openings should be considered as potentially hazardous and treatment should be considered. Strong rock overlying mined openings contributes to stability in proportion to its thickness. Support grouting and filling may be necessary to insure long-term stability.

Surface drainage generally should be collected in paved ditches and directed offsite to prevent infiltration of surface water. Positive control of reservoir seepage is required to prevent piping into solution features below reservoirs and beneath embankments. On the other hand, caution is called for to assure that foundation treatment such as grouting, cutoff walls, or diversion of runoff does not itself produce adverse effects on the groundwater regime.

Seismic stability of cavities usually is not a problem. However, grouting of open cavities in highly jointed rock can insure against block fallout caused by seismic events and prevent long-term progressive roof caving.

Groundwater levels, seepage conditions, and settlement should be monitored after construction to detect development of potentially hazardous conditions. Provisions should be made during construction for future remedial measures such as grouting beneath structures.

Complete records of all foundation treatment measures accomplished during construction should be made and maintained for future use in the event remedial measures are required.

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16. ABSTRACT *(200 words or less)*

About one-third of the continental United States is underlain by rocks that may present potential for ground collapse caused by caverns due to solution processes or mining activity. Four main functional issues concerning the integrity and proper functioning of foundations in areas with this potential are identified. They are: (1) Prediction of areas where there is a potential of ground collapse, (2) detection of cavities in areas where there is a potential for collapse, (3) evaluation of structural hazards posed by cavities, and (4) treatment of cavities to remedy structural problems. This report reviews pertinent current knowledge and practice related to these issues.

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