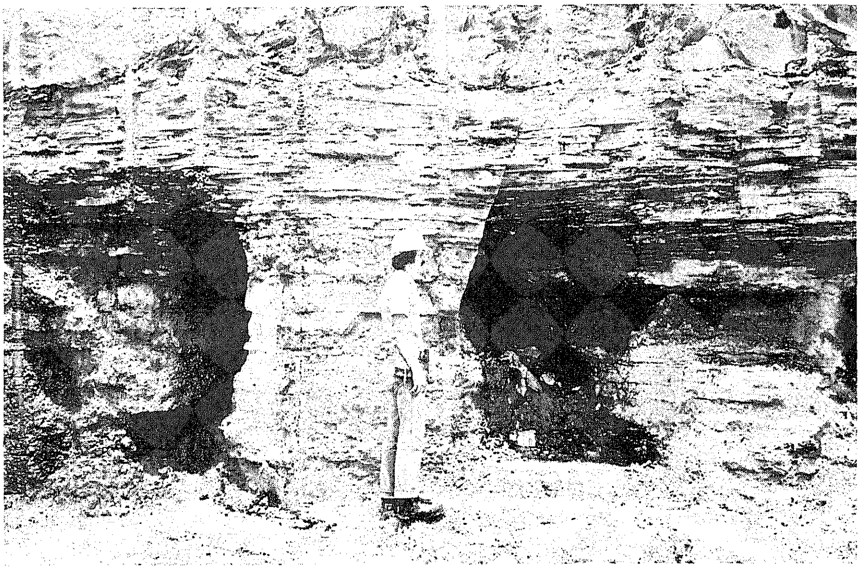


FIG. 5.4. Two Solution-enlarged Vertical Joints in a Horizontally Stratified Limestone Between Two Shale Strata (the Joints Intersect Behind the Face of a Deep Channel Excavated to the Lower Shale Stratum, as Depicted in the Photograph)

40 ft (12 m) deep in the limestone. Two of the caves intersected at right angles, forming a small chamber under the nearly completed reactor foundation.

The initial response of the regulatory authority was to order removal of the completed 8-ft (2.5-m) thick concrete mat foundation, followed by excavation to the cave level, approximately 34 ft (10 m) below the foundation level. The objective was to uncover any other caves that might be present and to replace all the excavation with concrete.

After more detailed study, including entry into the caves and mapping them, it was found that only a few such enlarged vertical joints were present. These caves and larger joints were cleaned out by a combination of manual mining and pressure washing, and then filled with concrete. This delayed construction of the reactor foundation, on the project critical path, by several months, with a total cost of more than $1 million. The alternative of removing the reactor foundation would have cost approximately 10 times more. Angle borings, oriented to identify and explore the solution enlargement of the vertical joints, would have disclosed the problem. Ironically, the geologic examination of an exposure of the same limestone nearby disclosed a similar rectilinear pattern of near vertical joints, most of which exhibited dissolution. This exposure could have warned the investigators of the need for angle borings to investigate the nature of the deeper portions of the joints.

Borehole photography and its successor, video imaging, provide a picture of the wall of an uncased borehole. While the photographic camera makes intermittent images, the video camera provides a continuous view of the hole as it is lowered or withdrawn (so long as the hole walls remain stable). A photograph of a video image of fractures in the wall of a 4-in. (100-mm) boring in limestone is seen in Fig. 5.5. Each of the two successive

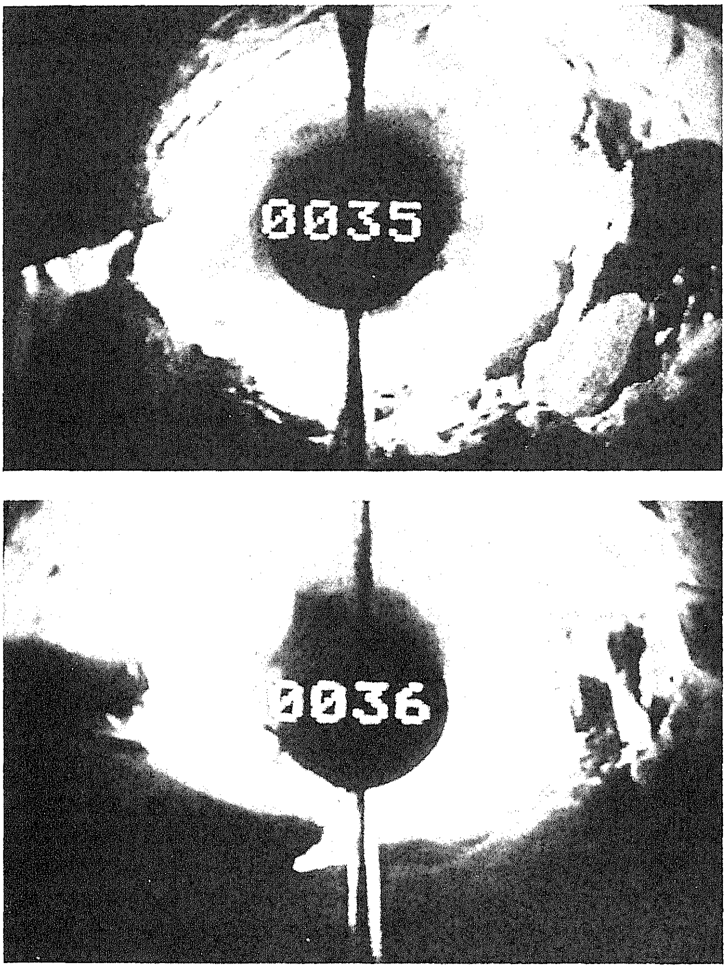


FIG. 5.5. Photographs of a Continuous Video Image of Fractures in the Wall of a 4-in. (100-mm) Diameter Borehole in Limestone

images depicts approximately 1 ft (300 mm) of hole centered about the depth indicator (in feet) in the image center. Fractures appear as irregular dark areas in the circular band of light. The vertical black line is the support for the downhole light. The continuous video image resembles the view a person would have riding in the front of a moving subway train; the walls are a circular band of light with a black spot (the camera) in the middle. Both the photographic and video cameras can be used below dirty groundwater by flushing the hole with clear water before and even during viewing. If the materials to be viewed are prone to caving, a casing is necessary to stabilize the hole walls. The hole is advanced 1 or 2 ft (300 to 600 mm) ahead of the casing and the camera or video camera is introduced immediately (but at some risk of damage or loss). The video record for such alternating casing advance and viewing contains small gaps, 1 or 2 in. (25- to 50-mm) wide. The detail that can be observed is limited by silt in the water below the water table. Fissures appear as dark shadows because the light does not penetrate fissures further than approximately twice their width.

The photographic and, particularly, the color video examination of the borehole makes it possible to evaluate closely fractured rock that produces no core recovery, to determine if fissures are open or clay-filled, and to determine if the voids encountered are isolated enlarged joints or large continuous caverns.

Even large diameter borings may not define the extent of slot and pinnacle formation. Test trenches and pits to the rock surface may be required. The size and depth of trenches and pits is limited by the equipment available, the strength of the overburden soil, the extent of the soft zone between the pinnacles, and the hardness of the rock. The minimum trench length should be greater than the distance between pinnacles, so that a full slot width is exposed. Pits and test trenches are expensive, and should be made after most of the other exploration work is complete in order to define the locations that would gain the most information. Such pits and trenches can be hazardous: measures are necessary to protect workers, livestock, and the curious passersby from harm. When the rock surface is below the piezometric level, large boreholes, trenches, and pits may be impractical or impossible, no matter how desirable.

All holes from invasive site investigation, such as borings and test pits, should be protected against surface water inflow. Casing extending above the ground surface should be sealed into the ground surface in all observation wells to prevent surface water from entering them. Open holes and pits are avenues for downward seepage for surface water that can aggravate erosion at the rock surface and possibly precipitate sinkhole development and collapse. Moreover, they are hazards to the curious who could fall into them. Test pits should be filled with compacted soil that is no more pervious that the surrounding soil. The borings and wells should be filled with sand cement grout after they have served their purposes.

5.6 GEOPHYSICAL EXPLORATION

5.6.1 The Geophysical Approach

Geophysical exploration involves measuring a force system in the earth and inferring boundaries between zones of similar response to those forces by the patterns of force change known as *anomalies*. The engineering behavior of the materials within each zone sometimes can be deduced from attenuation or distortion of the forces compared with what would be expected in a homogeneous material or by the velocity of propagation of the force wave. The force systems can be natural, such as gravity and the earth's magnetic field, or induced, such as an electrical current or a sound or shock wave. The methods are indirect in that, while the force patterns measured are related to the boundaries and engineering properties of the ground, they do not measure the boundaries, and most do not directly provide the data on physical properties needed for computing ground stability or for foundation design.

The methods that have proved useful in soil and rock exploration in limestone terrains are listed in Table 5.2. The notations of where the measurement is made have the following meaning: GS = made at or near the ground surface, BH = made at depth in a borehole.

TABLE 5.2. Geophysical Exploration

Natural Forces	Where Measured
Gravity	GS
Magnetic Field	GS
Self Potential	BH
Natural Gamma Ray Emission	BH
Induced Forces	
Ground Penetrating Radar	GS, BH
Seismic Refraction	GS, BH
Seismic Reflection	GS, BH
Direct seismic wave transmission	
Up-hole, down-hole seismic	BH to GS, BH to GS
Cross-hole seismic	BH to BH
Sonic Profiling	BH
Electrical Resistivity	GS, BH
Induced Electromagnetic Field	GS
Gamma Ray Attenuation	BH

The ground surface tests usually involve making measurements at many different locations, either along lines (*traverses*) or in a grid pattern. The results are interpreted from the variation of the force with the location on the site, and, in some cases, with the spacing between the sensing points. The ability of surface methods to identify solution features can be expressed by the *anomaly ratio*, R_a:

$$R_a = B / Z \tag{5.1}$$

where B = the anomaly width and Z = the depth from the ground surface (or the distance from the sensor to the anomaly). The wider the anomaly compared to its depth, the larger the ratio and the more likely that it will be detected. Combinations of downhole and surface geophysical measurements make it possible to increase the depth at which a defect can be identified. *Borehole geophysical probe* tests introduce groups of instruments (the probe) in a borehole as discussed in Section 5.7. These make it possible to test soils and rock at great depths below the ground surface, but typically at only small distances from the borehole.

5.6.2 Ground Surface Natural Force Fields

Gravity and magnetic surveys detect anomalies in those natural force fields by instruments at the earth's surface. Gravity reflects differences in soil and rock density; magnetism reflects minerals such as magnetite that distort the magnetic field. Gravity is useful in finding cavities in soil and rock, depending on the cavity size, its depth below the surface, and the density contrast. An open, air-filled cavity provides the best contrast; a dome cavity in soil overburden that is nearly filled with water or soft clay provides a poor contrast. Gravity is likely to be definitive if $R_a > 1$. Because gravity varies with the distance of the ground surface from the center of the earth, the interpretation of the data is more difficult in hilly and mountainous areas, even when the necessary corrections are made for the differences in ground surface elevation and for latitude.

Gravity exploration is useful in the early stages of site investigation to locate areas that are likely to exhibit significant near-surface dissolution or where there are large shallow ravelling-erosion domes in the soil.

Magnetic surveys similarly sometimes can identify anomalies in limestone formations. However, they generally have not been as useful as gravity.

5.6.3 Ground-penetrating Radar

Ground-penetrating radar uses pulses of radio frequency electromagnetic radiation to penetrate materials such as soil and rock and to generate reflections from materials of different density and electromagnetic response (the anomaly). The reflection data include the time elapsed between the emitted pulse and the receipt of the reflection, its return strength, and any phase changes. These data are analyzed and interpreted to find the depth and the lateral extent of the change. The depth of the radar penetration is limited by the power of the impulse and by the attenuation of the electromagnetic energy as it penetrates the ground. In sandy materials above the water table, penetration of more than 100 ft (30 m) is possible; in clays below the water table, only 5 to 20 ft (3 to 6 m) may be possible. Interpretation of the current forms of readout are somewhat subjective and require specialized training and experience. Better methods of processing and displaying the information are being developed that should make this method more useful in the future.

5.6.4 Electrical Resistivity

Both electrical resistivity and induced electromagnetic fields measure the electrical conductivity (or its inverse, the resistivity) of the soil and rock. Resistivity utilizes an electric current introduced into the ground by a pair of electrodes, usually at the ground surface. The resulting voltage difference is measured between two or more sensing electrodes that are also placed at the ground surface. Induced conductivity utilizes current flow at depth induced by an electromagnetic field at the ground surface. The effect is sensed at the ground surface from the changes in the strength and phase of the return electrical flux. The electrical conductivity of soils and rocks is related to the ionization of the electrolytes in the soil moisture and to the continuity of that moisture. The conductivity of dry soil or air is low; that of wet soil is high. Rock conductivity depends on the interconnected porosity of the rock as well as electrolytes in the groundwater. Both systems determine the effective conductivity of a significant volume of soil and rock, combining the effects of both low- and high-conductivity zones. The volume tested depends on the spacing and patterns of the electrodes or induction arrays compared to the geometry of the high- and low-conductivity strata or lenses. The depth and geometry of zones of different conductivity are deduced by empirical or mathematical analysis of the data. The nature of the soil and rock within each zone can sometimes be suggested by the computed conductivity (or resistivity), particularly if the geology of the formations underlying the site is known.

Cavities appear in two ways. Above the water table and filled with air, they have no conductivity. Below the water table they are conductive; wet clay filling is usually much more conductive than water filling. There may be little conductivity difference between saturated sand, saturated porous limestone, and a water-filled cavity, however.

As with the other surface geophysical methods, the size of the zone that can be identified depends on depth. The detectable anomaly ratio is usually between 0.5 and 1.5. Unlike seismic methods, described in the next section, shallow strata of high conductivity do not necessarily obscure a deeper stratum of low conductivity. Somewhat better resolution is possible with the electromagnetic induction system, particularly when there are sloping boundaries between different soil and rock formations. The electrical conductivity methods are also useful in estimating the average depth to continuous rock and usually the depth to groundwater. The groundwater is very conductive, while most rock formations, except porous limestones below the water table and saturated mudstones, have low conductivity.

The electrical conductivity is directly related to the potential corrosiveness of the soil and groundwater in contact with steel, such as piping and pile foundations: the higher the conductivity, the greater the corrosion potential of the ground.

5.6.5 Seismic Refraction

Seismic refraction usually involves the velocity of travel of a compressive shock wave induced at the ground surface or in a borehole by a hammer blow or a small explosion. The wave velocity depends on the density, modulus of elasticity, and Poisson's ratio of the soil or rock. As long as each successively deeper soil or rock layer has a higher wave transmission velocity, both the wave velocity in each stratum and the depth of the boundary between each can be calculated.

Two wave paths are shown in Fig. 5.6. The shortest is directly along the ground surface from the source of the shock to the detector or *geophone*. A longer path is down to the next stratum, along the surface of that stratum, and back up to the geophone. Although the path is longer, the time it takes for the pulse to reach the geophone could be shorter if the velocity of the wave in the deeper stratum is great and the thickness of the upper stratum is small. By varying the distance between the wave source and the geophone and measuring the time for the first wave to reach the detector, both the wave velocity in the upper stratum and the thickness of that stratum can be calculated.

A modulus of elasticity of each layer can be computed from its wave velocity. However, the modulus varies significantly with the amplitude and frequency of the shock wave. Therefore, the computed elastic modulus only applies to the particular shock wave induced by the test. The modulus that would be of use in foundation design likely will be one or two magnitudes smaller. Therefore, the induced seismic modulus value is of most use in comparing the rigidities of different strata. The type of soil or rock sometimes can be inferred from the shock wave velocity, particularly if the geophysical

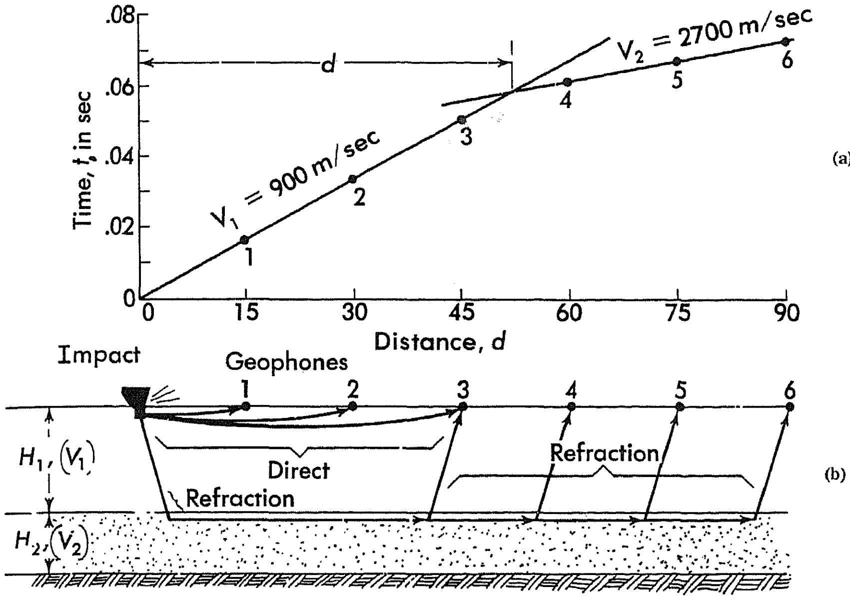


FIG. 5.6. Simplified Representation of Seismic Refraction, Using Ground-surface Shock Impulses and Ground-surface Geophones or Receptors [after Sowers (1979), p. 320–324]: a. Refraction and Simultaneous Direct and Refracted Signal Paths; b. Velocities of Alternate Wave Paths (Only the Signal that is Recorded First can be Identified; the Later Signals that Arrive at Each Geophone are Obscured by the Continuing Signals from the Wave Train that Arrives First)

results are correlated empirically with soil and rock test data from a nearby boring.

The method is most effective with strata of uniform thickness, parallel to the ground surface, although mathematical models for interpreting the effects of complex layering with sloping boundaries are available. If the boundaries are irregular, as is the case with a solutioned limestone surface, the data interpretation is highly subjective. When the solution-enlarged slots are wide compared to the depth to the bottom of the slots, the analysis defines a level between the maximum and average slot depth. If the slots are narrow, and the blocks of rock between are wide, the method is likely to identify the average depth to the block tops. Seismic reflection can also find the groundwater level if the seismic velocity below the water table level is greater than that of the unsaturated soil above it. The method seldom can find even large cavities in the overburden because the shock waves through the surface soil travel faster than through the cavity. It cannot find cavities in rock because the higher wave velocity in the sound rock above obscures the slower wave return of the cavity. Advanced dissolution that destroys the continuity of the wave travel in the rock may be reflected in lower rock velocities. In this way, wide pits or large cavities in the rock surface sometimes can be identified. However, if there is even a thin layer of intact rock above the solutioned zone, the lower velocity will be masked by the high velocity above. The ability of the method to sense irregularities decreases with increasing depth below the surface. Typically, an anomaly ratio of less than 1% is necessary.

5.6.6 Seismic Reflection

Seismic reflection senses the return of a compression wave from a deeper stratum or body having a different wave transmission velocity. The wave is induced in the ground by a large impact or small explosion at or near the ground surface. The return is sensed by a geophone close to the shock source at the surface, as shown in Fig. 5.7.

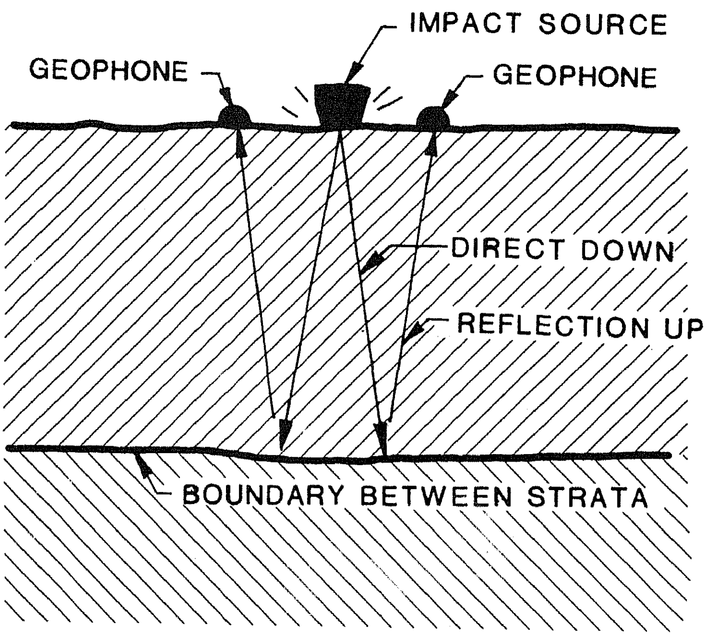
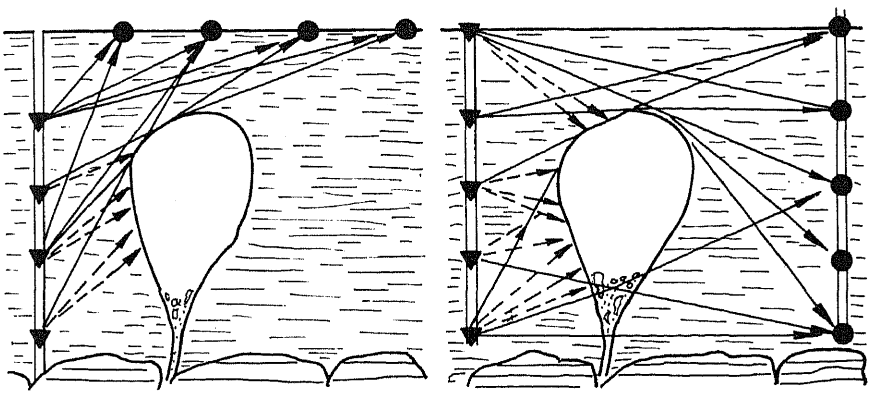


FIG. 5.7. Simplified Representation of Seismic Reflection Using Ground-surface Shock Impulses and Ground-surface Geophones or Receptors

The return is most useful in identifying the depth of very deep boundaries between strata of contrasting seismic velocity. It generally requires an anomaly ratio of 1 or more. The higher the velocity contrast, the better defined the results.

5.6.7 Direct Wave Transmission (Uphole, Downhole, and Crosshole)

Uphole, downhole, and crosshole seismic exploration measure the velocity of direct wave transmission between numerous points, both on the ground surface and in boreholes. Both wave source locations and the sensor locations are varied to provide several paths or rays of wave transmission through the body of soil or rock being explored (Fig. 5.8). Typically, several geophones are employed for each wave transmission reception. An air-filled cavity will not transmit the shock wave efficiently; therefore, the wave takes the longer path and the apparent straight line velocity is lower, indicating the cavity. With a number of wave paths, the location of the cavity can be found.



(a) (b)

FIG. 5.8. Simplified Representation of Direct Seismic Wave Transmission (the Signals From the Different Wave Paths can be Combined Mathematically, Utilizing the Depths and Directions of the Paths to Determine the Boundaries of the Void that Interrupts the Direct Transmission Paths; the Data are Combined by Tomographic Processing to Develop a Two-dimensional or Three-dimensional View of the Void): a. Uphole Direct Transmission with Sources in the Borehole and Receptors or Geophones on the Ground-surface and Downhole Interchanges Sources and Receptors; b. Crosshole Direct Transmission (the Sources are in One Hole and the Receptors or Geophones in the Other; these can be Reversed to Develop a Clearer Image)