CHAPTER 3
GEOLOGIC CONSIDERATIONS FOR INVESTIGATION AND DESIGN

3-1. Rock Types. The differing properties of various rock types by nature of their origin, lithology, and structure will influence the grouting conditions at a particular site. A thorough knowledge of the rock types present at the site, and their geologic history, is therefore essential for the design and treatment of the foundation. The exploration and grouting programs must be adapted to the site geologic conditions. Different rocks with the same general fracture permeability and void characteristics can be loosely grouped together. Examples of some of the more common rock types are listed, together with those general characteristics that could influence required foundation treatment.

a. Crystalline. Crystalline rock is an inexact but convenient term that identifies igneous and metamorphic as opposed to sedimentary rocks.

(1) Intrusive igneous rocks include granites, syenites, diorites, and gabbros. Some features commonly found in these rocks are sheet jointing, shear zones, dikes, and sills.

(2) Jointing in three directions is characteristic of intrusives. One set is usually near-horizontal (sheet or uplift jointing), and the other two are near-vertical and generally normal to each other. The spacing of sheet joints is frequently close near the surface but increases with depth.

(3) Grout take normally occurs in the joints and the fractures, and the volume is dependent on the size and continuity of the openings along the fractures. Certain metamorphic rocks such as gneisses would react in a manner similar to that of the granites. Grout takes in schists and slates are dependent on the presence and characteristics of associated jointing or fine fracturing. Most quartzites are highly fractured and would readily accept grout. Marble is a crystalline rock but should also be considered in the category of karstic formations since solution cavities should be anticipated.

b. Volcanics. Volcanics generally include the extrusive igneous rocks. Felsites, a group of very dense, fine-grained rocks, are extrusive and near-surface equivalents of granites, syenites, and other related crystalline rocks. In addition to granite-like jointing they may also exhibit columnar structure. Basalts are a group of very dense, dark, igneous rock. The jointing may be platy or columnar. Basalts in many flows commonly exhibit columns with three to six sides. Pumice and scoria are often associated with basalts. Pyroclastics, such as agglomerates and tuffs, are materials formed by explosive volcanic activity and consist of fragments torn loose by such explosions, or deposits of wind-borne ash. Large-scale engineering operations in pyroclastic rocks are generally difficult. Volcanics require extensive examination before engineering characteristics can be determined and will usually require special treatment. The presence of columnar jointing in lava flows tends to lower the strength of the mass as a whole, and extensive grouting can be expected. Permeabilities may be great in lava flows due to the extensive jointing which normally is present and due to the presence of piped vesicles and gas cavities. These features may transmit copious flows of water. In some cases, however, the joints are tight and/or filled and the rock mass may have a very low permeability. Each case must be evaluated individually to determine the need for and effectiveness of grouting.

c. Soluble Rocks. Limestone, dolomite, gypsum, anhydrite, and halite are included in this group. The principal defect in this rock group is solubility in varying degrees that can ultimately cause high mass permeability, slump, collapse, and sinks, resulting in karst topography.

(1) Limestones and dolomites are the most widespread of the soluble sediments. These rocks may be vuggy and may display a wide range of permeability as a unit. Limestone and dolomite are generally jointed and usually exhibit two or three distinct sets of jointing. Solutioning is frequently well developed along bedding planes and joints, and contacts with other rock types. Joints and cavities may be either filled or open and the size may vary greatly. Dependent upon the extent of jointing and cavities, extensive treatment and grouting can be anticipated.

(2) Anhydrite is pure calcium sulfate whereas gypsum is the hydrated form. Both are soft and fairly soluble in water. Both types may be jointed and have a varying number and size of solution cavities. The cavities often are filled with clay or other reworked material. Grout takes depend on the presence and characteristics of the joints and cavities.

(3) Halite (rock salt) is soft and soluble in water. The extremely soluble halite is not found in outcrop but may be found at depth. The principal engineering significance of halite is the effect its presence or proximity may have on the proposed project, such as solutioning and subsidence, in addition to effects on groundwater.

(4) Grouting in solutioned limestone and dolomite often meets with a mixed degree of success. Grouting will frequently dramatically reduce initial seepage. However, the seepage often has a tendency to increase with time after grouting is completed. The increased seepage is attributed to the erosion of void-filling materials that were not adequately removed before grouting. The erosion or piping of this unconsolidated material creates seepage windows in the grout curtain that become progressively larger and more prolific with time.

d. Clastic Sedimentary Rocks. Conglomerates, sandstones, siltstones, and shales are the principal types of clastic sedimentary rocks. The physical properties of sandstone, siltstone, and conglomerate depend on the degree and type of cementation. These coarser clastics may be tight and impermeable, or may be sufficiently porous and permeable to need treatment. Jointing would be the main concern in impermeable clastics as to need for treatment. The finer clastics, such as claystones and shales, are made up of clay minerals, various oxides, silica, fine particles of ordinary minerals, and some amount of colloidal and organic materials. These clastics may contain a great amount of water. Two shale types are cementation shale and compaction shale. Compaction shales usually contain no joints capable of being grouted. Cemented shales are more resistant to change and have engineering properties superior to those of the compaction type. Cemented to slightly metamorphosed shales are sufficiently brittle to react to structural changes and develop joints similar to those in sandstone.

e. Unconsolidated Materials. Unconsolidated materials include residual overburden derived from the weathering of the parent rock. Residual soils are in situ as opposed to transported sediments. The properties of the materials reflect to a certain extent the properties of the original material. Finer derivations of the parent rock, such as clays and silts, are generally impervious and would not require grouting. However, in certain instances where soluble rocks underlie the overburden, voids or very soft and loose material caused from the collapse of the overburden into the solution channels may require treatment. Transported sediments may include outwash deposits and alluvial deposits generally found in stream valleys, terrace deposits, and most glacial deposits. If the project design does not require removal of these deposits, grouting or other treatment may be required to reduce or control permeability and improve stability. Soil samples should be investigated by laboratory tests for permeability, gradation, and density.

3-2. Structural Geology.

a. Structure. The term "rock structure" refers to the spatial relationships of rocks and their discontinuities, and affects engineering projects in many ways. Folds and faults influence the selection of dam sites, and even such seemingly small matters as the spacing of joints may have an important bearing on the distribution of uplift pressures.

b. Folds. A common type of deformation is folding. The folded rocks often show considerable fracturing along the axis of the fold. The severity of engineering problems is dependent upon the complexity of the fold with relation to the type and geometry of the proposed structures and would include excavation, stability, and leakage problems.

c. Faults. Faults are fractures along which masses of rock have been moved in a direction parallel to the fault surface. The movement may vary from a few centimeters or less to many kilometers.

(1) Faults very rarely show a clean and uncomplicated break. The rocks will normally exhibit folding, fracturing, crushing, and grinding. Sometimes the walls exhibit polished and smoothly striated surfaces called slickensides. The rocks on the opposite sides of the fault surface may occasionally be

broken into angular fragments referred to as fault breccia. In addition to these mechanical effects, faults may result in channels for circulating water or may be impermeable and form groundwater barriers.

(2) Recognition of faults is of great importance because faults represent zones of weakness in the crust of the earth, and the presence of these zones would affect the engineering properties of a site, including seismological considerations, excavation, tunnel support, dam stability, and leakage problems.

d. Joints. Joints are almost universally present and are of considerable engineering importance for that reason. Joints offer channels for groundwater circulation, and joints below the groundwater table may greatly increase water problems. Joints may also exert an important influence on weathering and excavation characteristics.

e. Grouting Considerations. Since many rock types have a low primary permeability but a relatively high fracture and joint permeability, the importance of grouting the structural defects is apparent. The type of structural feature (e.g. fault, fold, joint) will dictate to a large extent the type and extent of excavation treatment and the grouting methods. The spacing and nature of the fractures (e.g. open, weathered, solutioned) influence the type of grout treatment selected, such as consolidation grouting and curtain grouting. The selection of a single-line or multiple-line curtain and the grout hole spacing are also affected. The orientation (dip and strike) of these features in relation to a structure influences the planned angle and direction of the grout holes and the drain holes. The depth of the fractures affects the depth of a grout curtain. The grout holes should intersect all the features, and each inclined or vertical feature should ideally be intersected by several holes at different depths. Faults may be gouge filled and impermeable, thereby forming a barrier, or may be open and carry groundwater. Joints may be filled or open, may have weathered or nonweathered faces, and may intersect and be connected over a wide area. The condition of the joints would affect the drilling, the cleaning, the pressure testing, and the grouting of the hole. Since structural features influence the grouting program so profoundly, the site exploration should be sufficiently thorough to base the design on actual site conditions.

3-3. Geohydrology. Almost all engineering projects are affected by subsurface water. The importance of subsurface water is especially obvious in respect to water retention structures. A thorough understanding of the regional and site specific groundwater conditions is necessary to safely design, construct, and operate these projects. A brief discussion of a few general principles follows. Application of the principles to specific problems such as foundation treatment and grouting can then be determined.

a. Porosity and Permeability. Almost all rocks contain pore spaces to some extent. To be permeable, however, pore spaces in rock must be interconnected and sufficiently large to allow the passage of water. Most sandstones are both porous and permeable. Shale, on the other hand, has a high porosity but the pores are limited to capillary sizes and water passage through the shale is extremely slow. Although intact shale is porous but impermeable, joints and other fractures permit the passage of water even though the water cannot readily pass through the interior of the joint-bounded rocks. Even in regions where the bedrock is granite or a similarly massive and impermeable rock, water occurs in fractures at least in limited quantities and to some depth. Understanding the nature of the joint system is of crucial importance in areas such as these.

b. Groundwater.

(1) Groundwater is the water in the zone of saturation. The upper limit of this zone is referred to as the water table. The depth to the water table may vary considerably depending on site conditions. The groundwater may be found either in continuous bodies or in several separate strata, and the thickness may vary considerably. Local saturated zones that may occur above the main water table are termed perched water.

(2) Local geology, permeability of the formations, including solutioning and fracturing, and recharge and movement within the zone are factors that affect aquifer characteristics. Any mass of permeable rock material from which a significant amount of water can be recovered is called an aquifer. Aquifers may be unconfined or confined. An unconfined aquifer occurs when the upper limit of the aquifer coincides with the water table, since the surface of the water is at atmospheric pressure. The hydraulic pressure at any level under this system is the same as the depth from the water table to the subject depth and may be expressed as hydraulic head in feet of water. Water under artesian conditions is under hydrostatic pressure and therefore rises in a well. When the pressure is sufficient to bring the water above the ground surface, a flowing artesian well occurs. Water that rises only to an intermediate level is a nonflowing artesian well.

(3) Artesian water also occurs in a similar fashion in jointed bedrock. Certain sets of joints may be more openly developed, and a large amount of water may gather in the joints under artesian conditions. A drill may pass through a few hundred feet of impermeable rock in which the joints are few and tightly closed. When the permeable, jointed zone is reached, the hydrostatic pressure at that depth causes the water to rise. The number of joints, as well as the degree of openness, normally decreases with depth, and the chance of penetrating a water-bearing zone is generally greatest in the upper portion of the bedrock.

c. Springs. Any natural surface emergence of water from a subterranean course is a spring. Many small springs represent water from rain or snow from higher ground that moves under gravitational force to a place of emergence. The course and flow rate of a spring depend on the permeability and structure of the material through which the water moves. Some springs flow upward with a measurable force, indicating that they are under pressure. Springs are most common in sandstones, cavernous carbonate rocks, vesicular lava flows, and highly jointed or fractured rocks of any kind. Some of the largest springs develop along the borders of karst regions.

d. Water Quality. The quality of the groundwater is primarily due to the mineralogical character of the reservoir rocks and their degree of solubility in water. The groundwater in limestone areas usually contains a large proportion of dissolved carbonates. Rock salt (halite) furnishes a ready source of chlorides, while gypsums and anhydrites supply quantities of sulfates. Water containing humic and other acids, dissolved sulfates, chlorides, and similar chemicals may act corrosively on steel and iron and may be injurious to grout and concrete. Ferrous iron in water may oxidize into an unsightly limonitic stain in certain cases. Iron may also lead to development of growths of iron bacteria. The source of the ferrous iron is generally rocks that contain pyrite or marcasite (iron sulfides). These minerals are common in many shales, especially carbonaceous shales. Water from such sources may also contain hydrogen sulfide. In areas where coal mining has occurred, both ground and surface water may be highly acidic.

e. Grouting Considerations.

(1) Since groundwater conditions have an important effect on design and construction, the regional and local conditions must be studied during the investigation stages so that potential problems may be evaluated. The grouting program should be designed for the existing groundwater conditions as well as for postconstruction conditions. Different methods and procedures may be employed, depending on the formation permeability, the depth to water table, and the type of aquifer present (confined and unconfined). These conditions affect the type of grout, the grouting procedure, the depth and extent of treatment, the spacing of holes, the need for a multiple- or single-line grout curtain, and the pressures that should be used.

(2) Aquifer conditions also have a direct bearing on the need for and type of drainage required. The chemistry of the groundwater should be considered with respect to the materials to be used in the proposed structure and to the grout to be used. Samples should be tested for pH and the chemistry analyzed. Springs in the construction area may require special treatment, including special grouting methods.

3-4. Investigation Methods.

a. Background.

(1) Investigations must be oriented toward identifying both the normal and the abnormal conditions and the discontinuities of even the smallest degree, because these conditions may control the design of the structure.

Special drilling procedures and equipment with detailed attention to the discontinuities and anomalies may be required. Besides the grouting design, the investigations are also used to determine the type and extent of excavation, groundwater conditions, and foundation preparation and treatment required.

(2) The type and scope of the drilling program are determined by the type of the proposed project and by the geology. The staged investigations may emphasize certain geologic features, such as stratigraphy and structure, groundwater investigations, or foundation analysis. Therefore, a variety of investigative methods may be required. These may include seismic and electrical resistivity surveys, core holes of all sizes, noncored holes, calyx holes for in situ foundation inspection, downhole logging techniques, swab tests, pump tests, pressure tests, and borehole photography. Each hole drilled should be designed to give the maximum information possible that is pertinent to the situation.

b. Site Conditions. Since grouting and drainage requirements and procedures are primarily based on geological conditions at a particular site and proposed structure, the exploration program must be comprehensive and accurate. If investigations confirm the presence of certain adverse geological conditions, treatment by excavation, grouting, or relocation of the site may need to be considered. The adverse conditions may include such things as the presence of soluble rocks, evidence of solution activity, prominent open joints, broken or intensively jointed rock, sheet jointing, open bedding planes, faulting, or unusual groundwater conditions. Besides drilling at the site as described in para c., and where no outcrop exist at the site, observations of the same formations should be made at nearby outcrops to get a better feel for joint and fracture spacing, continuity, and openings.

c. Drilling. Specific information on subsurface conditions is needed to plan the grouting program. To determine the scope and to estimate the costs of drilling and grouting operations in rock, information should be available on: overall geologic structure and stratigraphy; orientation, attitude, and spacing of joints; joint openings including type of any filler; boundaries of rock types; location of faults; location of broken zones, depth to sound rock, and position of water table. Sufficient drilling should be performed to delineate the above features. Tools such as borehole and television cameras and geophysical logging instruments should be used where needed to define subsurface conditions. Extensive use should be made of angle holes to give the maximum information possible concerning high angle jointing and faulting, particularly on the abutments where sheet or relief joints often occur. Each hole should be pressure tested and/or pumped to determine not only water take but to isolate the water-bearing or open zones in the hole. Therefore the hole should either be tested as it is drilled or tested by the use of a straddle packer after drilling is completed. If artesian conditions are encountered, these zones should be isolated and tested.

3-5. Test Grouting.

a. General. Field grouting tests prior to detailed design are very important. They provide the most accurate information for designing the complete grout program and for estimating the quantities to be required. The grout test can also be very valuable in evaluating the effectiveness that may be expected from the complete curtain. The grout test can also provide information as to which drilling method is most adaptable to the rock formation to be grouted.

(1) A test performed in each different geologic environment that the construction grouting will encounter is usually advisable if the differences are significant.

(2) The grout test may range from a very simple test of several different grout mixtures pumped into a few holes to determine the amount of each mix that can be injected, to a very comprehensive test that uses observation wells and pump tests before and after to evaluate the effectiveness of the grouting. The type of test selected should be based upon information needed, size of project, and complexity of geologic conditions. The grout test should be supervised in the field by the geologist responsible for designing the final grouting program. Testing should not include rock which will be excavated during the project construction.

b. Single Line Test Curtain.

(1) The simplest grouting test is to drill and grout a line of holes along the proposed grout line. Very careful records should be kept of each operation involved in the test. It is normally advisable to begin the grouting with a thin mixture, such as six parts water to one part cement, then gradually thicken the mixture if the hole continues to take grout. Care must be taken not to inject the hole with a mixture that is too thick and will stop the hole from taking grout prematurely. If this appears to be happening, immediately thin the mixture being pumped.

(2) Grouting of one hole is not an adequate grout test. Geologic conditions are normally far too variable for one hole to be representative. The number of holes used for a grouting test must be based on the designer's judgment and knowledge of the geologic conditions, but normally would include split spaced holes, that is, holes spaced equidistant between previously grouted holes.

(3) The main benefit from a single line grout test is to obtain an indication of the amount of grout the formation will take for estimating purposes and primary and split spacing distances. It also provides design information on drilling and grouting procedures to use.

c. Circle Grouting.

(1) A more comprehensive grout test is performed by grouting an area around a test well. This test will provide all of the information described in b above and will also allow an evaluation of grouting effectiveness by running pump tests before and after in the observation well.

(2) A test should be made with a radius of about 25 feet depending on rock properties. The grout holes drilled around the circumference of the circle should be spaced as planned for the final grout curtain. The holes should be drilled and grouted according to the split-spacing procedures normally followed in grouting.

(3) At least two lines of piezometers should be installed along lines radiating from the test well, which should be drilled at the center of the circle. It is normally of most benefit for a dam project to align the piezometer lines essentially parallel to the anticipated lines of flow from the impounded lake. Good locations for piezometers are one inside the circle, one in the grout curtain, and two outside the circle on each line.

(4) Pump tests should be made before and after the grout is placed. The differences in the permeability between the two tests are a reflection of the effectiveness of the grouting. The test well and the piezometers will sometimes become grouted up during the grouting operation, and reinstallation will be necessary after the grout is placed and before the final pump test is performed.

d. Multiple Line Grouting. A satisfactory grout test may be performed in some cases by drilling two or more lines of grout holes along the proposed grout curtain and a test well adjacent to the grout curtain. The test well should be pump tested before and after the grouting operation. A line of piezometers should be installed across the curtain to measure drawdown before and after grouting. The well or the piezometers may become clogged during the placement of grout, in which case new ones should be installed. Most of the information available from circle grouting tests is also available from this test. Multiple line grouting has the advantage of requiring fewer grout holes and less space to perform the test than required for circle grouting.

e. Observation Wells and Piezometers. Test wells and piezometers are useful in evaluating the effectiveness of the grout curtain.

(1) Well depth should be somewhat less than that of the grout holes. If the well is cored, the core should be carefully logged to note the location of fractured zones. The well should be pressure tested with straddle packers to locate permeable zones in the hole.

(2) Piezometers or observation wells should be installed so that the cone of depression can be established and the permeabilities of the rock

formation can be computed for the pumping tests before and after grout placement. The piezometers can normally be installed in smaller diameter holes such as NW (75.7 millimeters in diameter). Their depths, like those of the test wells, should be somewhat less than the depth of the grout holes, since the purpose of the piezometers is to provide an indication of the effect of the grout curtain on the permeability of the rock in which it is installed. The piezometers should be installed so that they are open to most of the column of rock in the hole. It is frequently acceptable to install piezometers by setting and grouting the casing into firm rock, then drilling to the planned depth and leaving the rock portion of the hole in open communication. The casing is left in place to serve as the piezometer pipe. Obtaining a seal between the casing and the rock is very important in this type of installation. This type of piezometer is actually a small-diameter observation well.

(3) A more sensitive piezometer installation consists of a small-diameter porous tube, or wellpoint, approximately 2-1/2 feet long connected to a small-diameter riser pipe. The porous tube, or wellpoint, is set near the bottom of the drilled hole, and sand is placed in the hole below, around, and above the tube. A seal of bentonite pellets is installed above the porous tube or wellpoint. This type of piezometer has two advantages over the open-hole installation described in (2) above: (a) It is considerably less likely to become grouted up during grouting operations because the grout will not travel far through the sand pack, and (b) it reflects changes more quickly in the water table in the surrounding rock because much less storage area is available for water in the hole.

f. Exploratory Holes. Exploratory holes drilled into the grout curtain are frequently advisable to evaluate grout intrusion into the fractures and fissures in the rock. It may be necessary to drill large-diameter core to fully recover grout in the fractures for evaluation. The chemical phenolphthalein ($C_{20}H_{14}O_4$) may be used to identify traces of grout in rock core. The exploratory holes should be pressure tested.

g. Evaluation of Results. Where test grouting is above the existing static water level, drawdown pump tests cannot be used to evaluate results. Consideration of the grout mixtures and pressures used, the reduction of take with split spacing, pump-in test results before and after grouting, and core holes as discussed in paragraph f are the principal methods for evaluation. Geophysical methods have also been used, but are not as reliable. In evaluating reduction of take with split spacing, it is helpful to reduce the data to a "unit take" such as take expressed as cubic feet of grout per foot of drill hole.

h. Determination of Drilling Procedures. One important piece of design information that should be obtained from a test grouting program is an evaluation of the best drilling method to be used to drill the grout holes at that particular site. Rotary and percussion drilling techniques should be evaluated. Various grout hole diameters should also be tried and evaluated. If these parameters are established during the test grouting program, they can be specified for the complete program and should eliminate the possibility of expensive contract modifications.