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Military Soils Engineering

Change 1

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Military Soils Engineering

1. Change FM 5-410, 23 December 1992, as follows:

Remove Old Pages	Insert New Pages
i through xxix	i through xxix
	2-29 through 2-38
7-1 through 7-8	7-1a through 7-8
	Glossary-29 through Glossary-30

2. A bar (|) marks new or changed material.

3. File this transmittal sheet in front of the publication.

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Field Manual 5-410

Military Soils Engineering

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Preface

SCOPE

Construction in the theater of operations is normally limited to roads, airfields, and structures necessary for military operations. This manual emphasizes the soils engineering aspects of road and airfield construction. The references give detailed information on other soils engineering topics that are discussed in general terms. This manual provides a discussion of the formation and characteristics of soil and the system used by the United States (US) Army to classify soils. It also gives an overview of classification systems used by other agencies. It describes the compaction of soils and quality control, settlement and shearing resistance of soils, the movement of water through soils, frost action, and the bearing capacity of soils that serve as foundations, slopes, embankments, dikes, dams, and earth-retaining structures. This manual also describes the geologic factors that affect the properties and occurrences of natural mineral/soil construction materials used to build dams, tunnels, roads, airfields, and bridges. Theater-of-operations construction methods are emphasized throughout the manual.

PURPOSE

This manual supplies engineer officers and noncommissioned officers with doctrinal tenets and technical facts concerning the use and management of soils during military construction. It also provides guidance in evaluating soil conditions, predicting soil behavior under varying conditions, and solving soil problems related to military operations. Military commanders should incorporate geologic information with other pertinent data when planning military operations, to include standing operating procedures.

The proponent of this publication is the US Army Engineer School. Submit changes for improving this publication on DA Form 2028 and forward it to: Commandant, US Army Engineer School, ATTN: ATSE-TD-D, Fort Leonard Wood, MO 65473-6650.

Unless otherwise stated, masculine nouns and pronouns do not refer exclusively to men.

DAMS

Dam sites are selected on the basis of topography, followed by a thorough geologic investigation. A geologic investigation should include, as a minimum—

- Soundness. Determine the soundness of underlying foundation beds and their ability to carry the designated load.

- Water integrity. Determine the degree of watertightness of the foundation beds at the dam location and the necessary measures, if any, to make the underlying geologic strata watertight.

- Duration of water exposure. Study the effect that prolonged exposure to water has on the foundation bedrock.

- Potential for quake activity. Determine the possibility of earth movement occurring at the dam site and what it takes to safeguard against such failures.

- Availability of materials. Investigate what natural materials are available near the site (potential quarries, sand, gravel, fill).

Generally, igneous rocks make the most satisfactory material for a dam foundation. Most igneous rocks are as strong as or stronger than concrete. However, many tuffs and agglomerates are weak. Solution cavities do not occur in igneous rocks because they are relatively insoluble; however, leakage will take place along joints, shear zones, faults, and other fissures. These can usually be sealed with cement grout.

Most metamorphic rocks have foundation characteristics similar to igneous rocks. Many schists are soft, so they are unsuitable as foundations for large, concrete dams. Marble is soluble and sometimes contains large solution cavities. As a rule, metamorphic rocks can be treated with cement grout.

Sandstones allow seepage through pores, joints, and other fissures. The high porosity and low permeability of many sandstones make them difficult to treat with cement grout. Limestone's solubility creates large underground cavities. Generally, the strength of shale compares favorably with that of concrete; however, its elasticity is greater. Shale is normally watertight.

TUNNELS

After determining the general location and basic dimensions of a tunnel, consider geological problems before designing and constructing it. Civil engineers dealing with tunnel construction understand the need for geological data in this field, so failure due to the lack of geological information seldom occurs. However, many failures do occur because engineers improperly interpret the available geological facts.

Folded Strata

Extensive fracturing often exists along the axis of folded rock. This presents difficulties in tunneling operations. In an anticline, such fractures diverge upward; in a syncline, they diverge downward. If a tunnel is placed along the crest of a fold, the engineer can expect trouble from shattered rock. In such a case, the tunnel may have to be lined its entire length. In a syncline, an engineer could face additional trouble, even with moderate fracturing. The blocks bounded by fracture planes are like inverted keystones and are very likely to drop. When constructing tunnels in areas of folded rocks, the engineer should carefully consider the geologic structure. If a tunnel passes through horizontal beds, the engineer should encounter the same type of rock throughout the entire operation. In folded strata,

many series of rock types can be encountered. Therefore, carefully mapping geological structures in the construction area is important.

Faulted Strata

As with folded rocks, the importance of having firm, solid rock cannot be stressed enough, not only for safety and convenience in working but also for tunnel maintenance after completion. If rock is shattered by faulting, the tunnel must be lined, at least in the crushed-rock area. Also, if the fault fissure extends to the surface, it may serve as a channel for rainwater and groundwater.

Groundwater Problems

Groundwater presence is often the main trouble source in tunnel construction. If tunnel grades cannot facilitate groundwater drainage, it may be necessary to pump throughout the tunnel. Therefore, it is necessary to have accurate information before beginning tunnel construction. Apply grout or cement, when possible, to solve water problems.

BRIDGES

Geological principles also apply in bridge construction. The weight of the bridge and the loads that it supports must be carried by the underlying foundation bed. In most cases, bridges are constructed for convenience and economy, so they must be located in specified areas. Therefore, engineers cannot always choose the best site for piers and abutments. Once construction begins, the bridge location cannot be easily changed and should only be done so under exceptional circumstances.

As a rule, bridges are constructed to cross over rivers and valleys. An older riverbed or other depression (caused by glaciation or river deposits) could be completely hidden below the existing riverbed. Problems could arise if such a buried valley is not discovered before bridge construction begins. For example, riverbeds contain many types of deposits, including large boulders. If preliminary work is not carefully done and correlated with geological principles, existing boulder deposits could be mistaken for solid bedrock.

BUILDINGS

Ground conditions at a building site may be one of three general types:

- On or near ground surface. Solid rock could exist at ground surface or so close to the surface that the foundation of the building can be placed directly on it.

- Below ground surface. Bedrock could exist below ground surface so that an economic, practical foundation can be used to support the building load.

- Far below ground surface. The nearest rock stratum could be so far below the surface that it cannot be used as a foundation bed. A building's foundation must be built on the material that forms the surface stratum.

If solid rock is present, its strength and physical properties must be determined. When the foundation consists of loose, unconsolidated sedimentary material, proper steps must be taken to solve the problem of subsidence. Structures that are supported on bedrock, directly or through piles or piers, will settle by extremely small amounts. If a foundation has been supported in unconsolidated strata, appreciable settlement can be expected.

QUARRY OPERATIONS

Natural sand and gravel are not always available, so it is sometimes necessary to produce aggregate by quarrying and processing rock. Quarrying is normally done only where other materials of

adequate quality and size cannot be obtained economically and efficiently.

Many rock types are suitable for construction, and they exist throughout the world. Therefore, the quality and durability of the rock selected depend on local conditions. The following rock types are usually easy to quarry. They are also durable and resistant to weathering.

- Granite. As a dimension stone, granite is fairly durable and has a texture and a color that are desirable for polishing. As a construction material for base courses and aggregate, it is not as desirable as some of the denser igneous rocks.

- Felsite and rhyolite. These are durable and make good aggregate for base courses. They are not suitable for concrete aggregate.

- Basalt. The dense, massive variety of basalt is excellent for crushed rock, base course, and bituminous aggregate. It is very strong and durable. Due to basalt's high compressive strength, processing it may be more difficult than processing other rocks.

- Sandstone. Few sedimentary rocks are desirable for construction due to their variable physical properties, but sandstone is generally durable. However, deposits must be evaluated individually, due to the variable nature of grains and cement present in the rock.

- Limestone. Limestone is widely used for road surfacing, in concrete, and for lime production. It is a good, all-around aggregate.

- Gneiss. Most varieties of gneiss have good strength and durability and make good road aggregate.

- Quartzite. Quartzite is hard and durable, so it is an excellent rock for construction. However, it can be difficult to quarry.

- Marble. The texture and color of marble make it desirable for dimension stone. It can also be used for base course and aggregate material.

Factors that enhance the easy removal of rock often diminish its suitability for construction. Strong, durable, unweathered rock usually serves best for embankment and fill, base and surface course material, concrete aggregate, and riprap. However, these rocks are the most difficult to quarry or excavate.

Soils continuously change. Weathering, chemical alteration, dissolution, and precipitation of components all occur as soils accumulate and adjust to their environment. Particle coatings and natural cements are added and removed. Soluble components wash downward (leach) or accumulate in surface layers by evaporation. Plants take root and grow as soil profiles develop. These changes tend to become more pronounced with increasing age of the soil deposit. These possible alterations to the sediment may affect its utility in construction. The soils of natural geological deposits are commonly used as construction materials.

Section IV. Applied Military Geology

The science and applied art of geology is an important component of military planning and operations. Today, computers, satellites, geographic information systems, geographic positioning systems, and similar technology have catapulted the art and science of geology as an everyday tool for military commanders and engineers.

MILITARY GEOGRAPHIC INTELLIGENCE

The purpose of geographic intelligence is to obtain data about terrain and climate. Commanders use the information to make sound decisions and soldiers use it to execute their missions. In planning an operation, commanders and their staff analyze the effects that terrain and climatic conditions will have on the activities of friendly and enemy forces. Knowledge of how geology controls and influences terrain is helpful for classifying and analyzing terrain and terrain effects. When provided with adequate geographic and geologic intelligence, commanders are able to exploit the advantages of the terrain and avoid or minimize its unfavorable aspects. Data on soil movement, the presence of hard rock, and the kind and distribution of vegetation is needed when considering concealment and cover, cross-country travel, and field fortifications. Strategic intelligence studies prepared by Department of Defense agencies provide detailed geographic and terrain information (*Table 2-2*) useful for compiling and analyzing geographic intelligence.

Maps and Terrain Models

Maps are a basic source of terrain information. Geologic maps show the distribution, age, and characteristics of geologic units. They may also contain cross sections that show the subsurface occurrence of rock and soil. Maps may have text explaining physical properties; engineering properties; and other information on natural construction materials, rock formations, and groundwater resources. Soil maps are commonly presented under an agricultural classification but may be used for engineering purposes after they have been converted to engineering nomenclature.

A terrain model is a three-dimensional graphic representation of an area showing the conformation of the ground to scale. Computer-generated images have recently been developed that display two-dimensional form images in three-dimensional form for viewing from any angle.

Remote Imagery

Aerial and ground photography and remote imagery furnish information that is not readily available or immediately apparent by direct ground or aerial observation. Examples are infrared photography and side-looking radar. Imagery permanantly preserves information so that it is available for later study. Photographs normally depict more recent terrain features than available maps.

Terrain Classification

Land forms are the physical expression of the land surface. For terrain intelligence purposes, major land forms are arbitrarily described on the basis of local relief (the difference in elevation between land forms in a given area).

GEOLOGY IN RESOLVING MILITARY PROBLEMS

To apply geology in solving military problems, personnel must first consider geologic techniques and uses and then determine how to acquire the needed information. Commanders can use geology in three ways—geologic and topographic map interpretation, photo interpretation, and ground reconnaissance.

Maps

Combination topographic and geologic maps can tell commanders and engineers what the ground looks like. Map information should be made available early in operation planning. The success of many

Table 2-2. Reports for geographic/terrain intelligence

Report Title	Report Application
Imagery interpretation	Planning combat and support operations Planning recon activities Supporting requests for terrain intelligence Analyzing areas of operations Planning terrain studies
Terrain study on soils	Supporting communications planning Executing movement, maneuver operations Planning combat operations (construction of landing strips, maintenance of culverts) Selecting avenues of approach
Terrain study on rocks	Planning movement, maneuver operations Planning combat operations (construction, maintenance, and destruction of roads, bridges, culverts, and defensive installations) Selecting avenues of approach
Terrain study on water resources	Selecting locations of and routes to water points Planning combat operations (street crossing, bridging) Supporting logistics planning
Terrain study on drainage	Supporting communications planning Planning combat operations (constructing roads, fortifications, and fjords) Supporting river crossings and cross-country movement
Terrain study on surface configuration	Supporting communications planning Planning observation posts and recon activity Planning tactical operations and executing tactical objectives Planning barrier and denial operations Planning artillery support
Terrain study on the state of the ground	Planning movement, maneuver operations Planning ADM activity Planning combat operations (constructing, maintaining, and repairing roads, fjords, landing strips, and fortifications) Planning logistics support
Terrain study on construction suitability	Planning combat operations (constructing fortifications, landing strips, camouflage, obstacles, and a CP's supply installations) Selecting construction supply-point locations
Terrain study on coasts and landing beaches	Planning amphibious operations (preparing and removing obstacles and fortifications) Planning recon activity Planning port construction
Terrain study on cross-country movement	Planning and executing maneuver, movement operations Planning logistics support Planning barrier and denial operations Planning engineer combat operations
Terrain study on airborne landing areas	Planning area-clearing support Planning recon activity Planning combat operations (constructing and repairing landing strips) Selecting helicopter landing zones

military operations depends on the speed of required advance construction. Speed, in turn, depends on completely understanding the needs and adequately planning to meet those needs in a particular area. Topographic maps are important sources of information on slope and land forms. One problem in using a topographic map is that some relief or roughness may be hidden between the contour lines. Generally, the larger the interval between contour lines and the smaller the

scale of the map, the more the relief is hidden. Conversely, the smaller the contour intervals and the larger the scale of the map, the less the relief is hidden.

Photographic Interpretation

Many principles that make a geologic map useful for estimating the terrain situation also apply to the usefulness of aerial photographs. The interpreter's skill is very important. Without a professional photo interpretation and the knowledge of geologic process and forces, a great deal of information may be overlooked. In preparing terrain intelligence, aerial photographs alone will not provide enough information. Geologic maps must also be available. Aerial photographs are completely reliable for preparing tactical terrain intelligence. However, the usefulness of aerial photographs varies with the scale of the report being prepared.

Reconnaissance

Interpretation of the land for military purposes can be accomplished by studying maps and can be even more accurate by adding photographs. Using maps or photographs is highly effective, but it cannot compare in accuracy to actual ground observation. In a tactical situation, such as when attacking a defended position, the knowledge of the terrain behind the position is vital for planning the next move. Terrain may be different on the side that cannot be seen. Generally, the difference is expressed in the geology of the slope that can be observed. By combining ground observation and reconnaissance by a trained observer (geologist) with aerial and map interpretation, the commander can plan ahead. Reconnaissance of secure territory can be used to an even greater advantage when developing the area of occupation or advancement.

REMOTE IMAGERY

The major kinds of remotely sensed imagery are photography, radar, and multispectral or digital scanner imagery. Since the 1930s, various worldwide agencies have acquired a large amount of remote imagery. The quality, scale, and nature of the coverage vary considerably because new techniques and equipment are being developed rapidly. Remote imagery can be—

- Generated quickly in a specified time.

- Displayed accurately.

- Produced in a useful and storable format.

- Produced in volume (*Table 2-3*).

High-altitude aircraft and spacecraft imagery are desirable for regional geologic mapping and delineating major structural features. Stereo coverage of low-, medium-, and high-altitude photography is used for detailed geologic mapping of rock units, structure, soil type, groundwater sources, and geologic hazards such as slope failure, sinkholes, fracturing zones, and flooding.

FIELD DATA COLLECTION

Field data collection is necessary to—

- Supplement existing information obtained from published and unpublished literature.

- Obtain site-specific, detailed information that describes the local geology.

Mission constraints, such as time, resources, weather, and political climate, limit the amount of field investigation that can be conducted. The following methods and procedures, which were designed primarily for civilian peacetime

Table 2-3. Sources of remote imagery

Procurement Platform	Imagery Format	Scale	Coverage	Source Agency
Low-, medium-, and high-altitude aircraft	Black and white or color stereo pairs of aerial photos of high resolution	1:12,000 1:125,000	Limited worldwide (low altitude, 1942 to present; high altitude, 1965 to present)	USGS, EROS data center, Sioux Falls, SD
Low-, medium-, and high-altitude aircraft	Black and white, color, color IR, black and white IR, thermal IR, SLAR, multiband imagery (reproductions of imagery are available to all US military organizations and US government agencies)	1:1,000 1:100,000	Partial to full coverage of most foreign countries from late 1930s to present	DIA, ATTN: DC-6C2, Washington, DC 20301
Low-, medium-, and high-altitude aircraft	Black and white, color IR	Main scales: 1:20,000 1:40,000 Black and white: 1:20,000 to 1:120,000	Black and white: 80% of US Color IR: Partial US	ASCS, Aerial Photo Field Office, PO Box 30010, Salt Lake City, UT 84130
Unmanned satellites ERTS LANDSAT 1-5 MSS— Band 4: green (0.5-0.6 m) Band 5: red (0.7-0.8 m) Band 6: near IR (0.7-0.8 m) Band 7: near IR (0.8-1.0 m)	Black and white, color composite (IR), color composition generation, 7 and 9—track computer—compatible tapes (800 and 1,600 bpi)	1:250,000 1:3,369,000	Worldwide coverage, complete earth's surface coverage every 18 days, 1972 to present; every 9 days, 1975 to present	EROS data center
Manned spacecraft Skylab with S-190A multispectral camera and S-190B system, single lens (earth terrain camera)	S-190A: black and white, black and white IR, color IR, high resolution color S-190B: black and white, color, stereo pairs	S-190A: 1:1,250,000 1:2,850,000 S-190B: 1:125,000 1:950,000	Limited worldwide coverage	EROS data center

projects, serve as a guide for the kinds of geologic information that can be obtained in field investigation.

All available geologic information (literature, geologic and topographic maps, remote sensing imagery, boring logs, and seismic data relative to the general area of the project) should be collected, identified, and incorporated into the preliminary study for the project. This preliminary study should be completed before field investigations begin. A preliminary study allows those assigned to the project to become familiar with some of the engineering problems that they may encounter. Geologic information available in published and unpublished sources must be supplemented by data

that is gathered in field investigations. Some of the most reliable methods available for field investigation are boring, exploration excavation, and geophysical exploration.

Boring

Borings are required to characterize the basic geologic materials at a project. They are broadly classified as disturbed, undisturbed, and core. Borings are occasionally made for purposes that do not require the recovery of samples, and they are frequently used for more than one purpose. Therefore, it is important to have a complete log of every boring, even if there is not an immediate use for some of the information. Initial exploration phases should concentrate on providing overall information about the site.

Exploration Excavation

Test pits and trenches can be constructed quickly and economically using bulldozers, backhoes, draglines, or ditching machines. Depths are normally less than 30 feet. Side excavations may require shoring, if personnel must work in the excavated areas. Exploratory tunnels allow for detailed examination of the composition and the geometry of rock structures such as joints, fractures, faults, and shear zones. Tunnels are helpful in defining the extent of the marginal strength of rock or adverse rock structures that surface mapping and boring information provide.

Geophysical Exploration

Geophysical exploration consists of making indirect measurements from the earth's surface or in boreholes to obtain subsurface information. Boreholes or other subsurface explorations are needed for reference and control when using geophysical methods. Geophysical explorations are appropriate for rapidly locating and correlating geologic features such as

stratigraphy, lithology, discontinuities, structure, and groundwater.

EQUIPMENT FOR FIELD DATA COLLECTION

The type of equipment needed on a field trip depends on the type of survey being conducted. The following items are always required:

- Hammer. This is usually a geologic hammer, and it is used to break or dig rock and soil and to prepare samples for laboratory examination. A hammer is also useful for determining the strength and resistance of the rock and the toughness of the grains.

- Hand lens. A hand lens is a small magnifying glass, usually 10X power. It is used to examine individual mineral grains of rock for identification, shape, and size.

- Dilute hydrochloric (HCl) acid. One part concentrated HCl acid to four parts water is used to determine carbonate rocks. Dilute acid is preferred because the degree of its reaction with different substances is seen more easily.

- Brunton compass. One of the most important pieces of equipment to the field geologist is the Brunton compass. This instrument is an ordinary magnetic compass with folding open sights, a mirror, and a rotating dial graduated in degrees or mils. In some cases, the dial is numbered to 360 degrees, while in others, the dial may be graduated in 90-degree quadrants. A compass helps measure dips, slopes, strikes, and directions of rock formations.

- Base map. A base map is essential in all types of field work except when the plane-table-and-alidade method is used.

GEOLOGICAL SURVEYING

The instruments and methods of geological surveying are numerous and varied. Instruments used on a particular project depend on the scale, time, detail, and accuracy required.

Pace-and-Compass Method

The pace-and-compass method is probably the least-accurate procedure used. The survey is conducted by pacing the distance to be measured and determining the angle of direction with the compass. The field geologist records elevations on a topographic map, when it is available. When a topographic map or a good equivalent is unavailable, an aneroid barometer or some type of accurate altimeter is used to record elevations.

Plane-Table-and-Alidade Method

When accurate horizontal and vertical measurements are required, the plane-table-and-alidade method is used. The equipment consists of a stadia rod, a tripod, a plane table, and an alidade. Sheets of heavy paper are placed on the plane table to record station readings. After recording the stations, the geologist places formation contacts, faults, and other map symbols on the paper. This information can later be transferred to a finished map. The alidade is a precision instrument consisting of a flat base that can easily be moved on the plane table. The straight edge, along the side of the flat base and parallel to the line of sight, is used to plot directions on the base map. The alidade also consists of a telescopic portion with a lens that contains one vertical hair and three horizontal hairs (stadia hairs). The vertical hair is used to align the stadia rod with the alidade. The horizontal hairs are used to read the distance to the rod. Vertical elevations are determined from the stadia distance and the vertical angle of the points in question.

Brunton-Compass-and-Aerial-Photo Method

A Brunton compass and a vertical aerial photo provide a rapid, accurate method for geological surveys. The aerial photo is used in place of a base map. Contact, dips and strikes, faults, and other features may be plotted directly on the aerial photo or on a clear acetate overlay. Detailed notes of the geological features must be kept in a separate field notebook. If topographic maps are available, they will supplement the aerial photo and eliminate the need for an aneroid barometer. A topographic map may be used for the base map and to plot control for horizontal displacements.

Plane-Table-, Mosaic-, and-Alidade Method

A mosaic of aerial photos may be used with a plane table and an alidade, thus eliminating the base map. This procedure is used to eliminate the rod holder and to accelerate the mapping. By using a plane table and an alidade as a base, horizontal distance does not have to be measured; and the surveyor can compute vertical elevation. The surveyor—

- Reads the angle of variation from the horizontal distance.

- Scales the distance from the map.

- Finds the difference by trigonometric calculations.

This method is faster than the normal plane-table method, but it is not as accurate.

Photogeology Method

Photogeology is the fastest and least-expensive method of geological surveying. However, a certain amount of accuracy and detail is sacrificed. This type of survey is normally used for reconnaissance of

large areas. When a geologic map is constructed from aerial-photo analysis alone, it shows only major structural trends. After a preliminary office investigation, a geologist may go to the field and determine detailed geology of particular areas.

CHAPTER 7

Movement of Water Through Soils

The movement of water into or through a soil mass is a phenomenon of great practical importance in engineering design and construction. It is probably the largest single factor causing soil failures. For example, water may be drawn by capillarity from a free water surface or infiltrate through surface cracks into the subgrade beneath a road or runway. Water then accumulated may greatly reduce the bearing capacity of subgrade soil, allowing the pavement to fail under wheel loads if precautions have not been taken in design. Seepage flow may be responsible for the erosion or failure of an open cut slope or the failure of an earth embankment. This chapter concerns the movement of water into and through soils (and, to some extent, about the practical measures undertaken to control this movement) and the problems associated with frost action.

Section I. Water

Knowledge of the earth's topography and characteristics of geologic formations help the engineer find and evaluate water sources. Water in the soil may be from a surface or a subsurface source. Surface water sources (streams, lakes, springs) are easy to find. Finding subsurface water sources could require extensive searching. Applying geologic principles can help eliminate areas where no large groundwater supplies are present and can indicate where to concentrate a search.

HYDROLOGIC CYCLE

Water covers 75 percent of the earth's surface. This water represents vast storage reservoirs that hold most of the earth's water. Direct radiation from the sun causes water at the surface of rivers, lakes, oceans, and other bodies to change from a liquid to a vapor. This process is called *evaporation*. Water vapor rises in the atmosphere and accumulates in clouds. When enough moisture accumulates in the clouds and the conditions are right, water is released as *precipitation* (rain, sleet, hail, snow). Some precipitation occurs over land surfaces and represents the early stage of the land hydrologic cycle. Precipitation that falls on land surfaces is stored on the surface, flows along the surface, or flows into the ground as *infiltration*. Infiltration is a major source of groundwater and is often referred to as *recharge*, because it replenishes or recharges groundwater resources.

The hydrologic cycle (*Figure 7a, page 7-1b*) consists of several processes. It does not usually progress through a regular sequence and can be interrupted or bypassed at any point. For example, rain might fall in an area of thick vegetation, and a certain amount of this moisture will remain on the plants and not reach the ground. The moisture could return to the atmosphere by direct evaporation, thereby causing a break in the hydrologic cycle. For the military engineer, the two

most important states of this cycle are those pertaining to surface runoff and water infiltration.
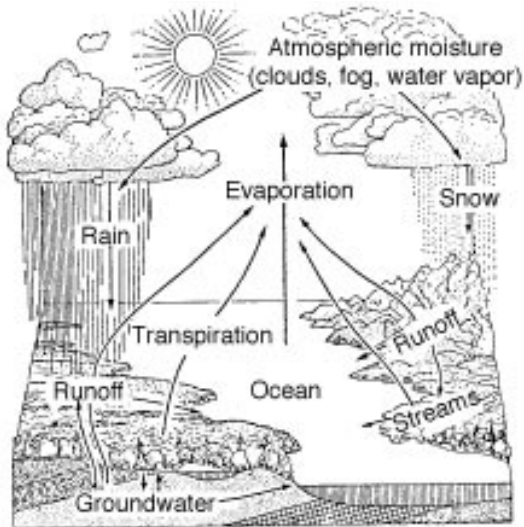
Figure 7a. Hydrologic cycle

SURFACE WATER

Streams and lakes are the most available and most commonly used sources for military water supplies. However, other subsurface water sources should be considered because long-term droughts could occur. Water naturally enters through soil surfaces unless they are sealed; and sealed surfaces may have cracks, joints, or fissures that allow water penetration. Surface water may also enter from the sides of construction projects, such as roads or airfields.

Surface water is not chemically pure. It may contain sediment, bacteria, or dissolved salts that make the water unfit for consumption. Natural contamination and the pollution that man causes are also dangerous and occur in surface water. Test all surface water for purity and take proper precautions before using it.

Streams

Streams normally supply an abundant quantity of water for the initial phase of a field operation. The water supply needs to be adequate for the time of year the operation is planned. For a long-term supply, you must learn the permanent status of the stream flow.

Lakes

Most lakes are excellent sources of water. They serve as natural reservoirs for storing large amounts of water. Lakes are usually more constant in quality than the streams that feed them. Large lakes are preferable because the water is usually purer. Shallow lakes and small ponds are more likely to be polluted or contaminated. Lakes located in humid regions are generally fresh and permanent. Lakes in desert regions are rare but can occur in basins between mountains. These lakes could have a high percentage of dissolved salts and should not be considered as a permanent source of water.

Swamps

Swamps are likely to occur where wide, flat, poorly drained land and an abundant supply of water exist. A large quantity of water is usually available in swamps; but it may be poor in quality, brackish, or salty.

SPRINGS AND SEEPS

Water that naturally emerges at the surface is called a *spring* if there is a distinctive current, and a *seep* if there is no current. Most springs and seeps consist of water that has slowly gravitated from nearby higher ground. The water's underground course depends on the permeability and structure of the material through which it moves. Any spring that has a temperature higher than the yearly average temperature of a given region is termed a *thermal spring* and indicates a source of heat other than the surface climate.

Gravity Springs and Seeps

In gravity springs and seeps, subsurface water flows by gravity, not by hydrostatic pressure, from a high point of intake to a

lower point of issue. Water-table springs and seeps are normally found around the margin of depressions, along the slope of valleys, and at the foot of alluvial fans. Contact springs appear along slopes, and may be found at almost any elevation depending on the position of the rock formations.

Artesian Springs

When water is confined in a rock layer under hydrostatic pressure, an artesian condition is said to exist. A well drilled into an aquifer where this condition is present, is called an *artesian well* (*Figure 7b*). If the water rises to the surface, it is called an *artesian spring*. Certain situations are necessary for an artesian condition to exist—

- There must be a permeable aquifer that has impervious layers above and below it to confine the water.

- There must be an intake area where water can enter the aquifer.

- A structural dip must exist so that hydrostatic pressure is produced in the water at the lower areas of the aquifer.

GROUNDWATER

Groundwater or *subsurface* water is any water that exists below the earth's surface. Groundwater is located in two principle zones in the earth's surface—aeration and saturation (*Figure 7c, page 7-1d*).

The zone of aeration consists of three major belts—soil moisture, intermediate, and capillary fringe. As water starts infiltrating the ground surface, it encounters a layer of organic matter. The root systems of plants, decaying organic material, and the small pores found within the upper soil zone hold some of the water in suspension. This shallow layer is called the *soil moisture* belt. The water passes through this belt and continues downward through the *intermediate* belt. The pore spaces in this belt are generally larger than those in the soil moisture belt, and the amount of organic material is considerably reduced. The intermediate belt contains voids so it does not hold water, and the water gradually drains downward. The next belt is called the *capillary fringe*. Most deep-rooted plants sink roots into this area.
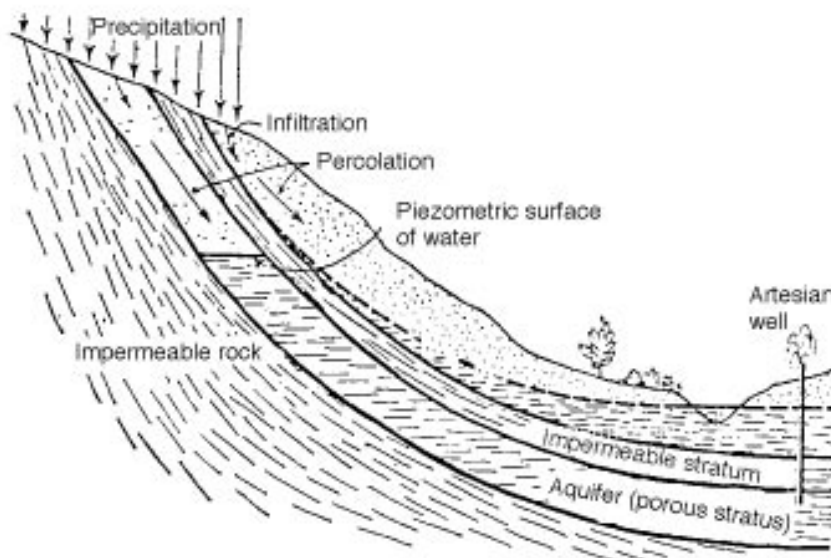
Figure 7b. Artesian groundwater
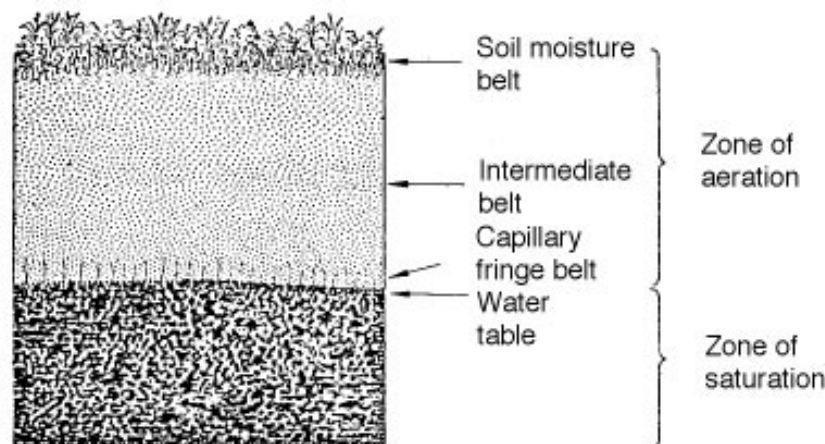
Figure 7c. Groundwater zones

The water table is the contact between the zone of aeration and the zone of saturation. It fluctuates up and down, depending on the recharge rate and the rate of flow away from the area. The pores are filled with water in the zone of saturation.

Free, or Gravitational, Water

Water that percolates down from the surface eventually reaches a depth where there is some medium that restricts (to varying degrees) the further percolation of the moisture. This medium may be bedrock or a layer of soil, not wholly solid but with such small void spaces that the water which leaves this zone is not as great as the volume or supply of water added. In time, the accumulating water completely saturates the soil above the restricting medium and fills all voids with water. When this zone of saturation is under no pressure except from the atmosphere, the water it contains is called free, or gravitational, water. It will flow through the soil and be resisted only by the friction between the soil grains and the free water. This movement of free water through a soil mass frequently is termed seepage.

The upper limit of the saturated zone of free water is called the groundwater table, which varies with climatic conditions. During a wet winter, the groundwater table rises. However, a dry summer might remove the source of further accumulation of water. This results in a decreased height of the saturated zone, for the free water then flows downward, through, or along its restricting layer. The presence of impervious soil layers may result in an area of saturated soil above the normal groundwater table. This is called a "perched" water table.

Hygroscopic Moisture

When wet soil is air-dried, moisture is removed by evaporation until the hygroscopic moisture in the soil is in equilibrium with the moisture vapor in the air. The amount of moisture in air-dried soil, expressed as a percentage of the weight of the dry soil, is called the hygroscopic moisture content. Hygroscopic moisture films may be driven off from air-dried soil by heating the material in an oven at 100 to 110 degrees Centigrade (C) (210 to 230 degrees Fahrenheit (F)) for 24 hours or until constant weight is attained.

Capillary Moisture

Another source of moisture in soils results from what might be termed the capillary potential of a soil. Dry soil grains attract moisture in a manner

similar to the way clean glass does. Outward evidence of this attraction of water and glass is seen by observing the meniscus (curved upper surface of a water column). Where the meniscus is more confined (for example, as in a small glass tube), it will support a column of water to a considerable height. The diagram in *Figure 7-1* shows that the more the meniscus is confined, the greater the height of the capillary rise.
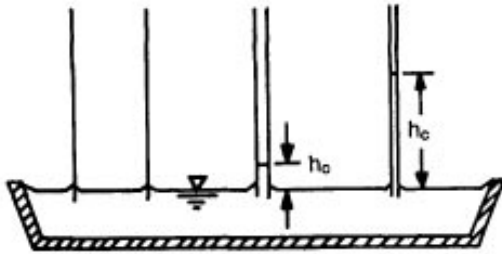
Figure 7-1. Capillary rise of moisture

Capillary action in a soil results in the "capillary fringe" immediately above the groundwater table. The height of the capillary rise depends on numerous factors. One factor worth mentioning is the type of soil. Since the pore openings in a soil vary with the grain size, a fine-grained soil develops a higher capillary fringe area than a coarse-grained soil. This is because the fine-grained soil can act as many very small glass tubes, each having a greatly confined meniscus. In clays, capillary water rises sometimes as high as 30 feet, and in silts the rise is often as high as 10 feet. Capillary rise may vary from practically zero to a few inches in coarse sands and gravels.

When the capillary fringe extends to the natural ground surface, winds and high temperatures help carry this moisture away and reduce its effects on the soil. Once a pavement of watertight surface is applied, however, the effect of the wind and temperature is reduced. This explains the accumulation of moisture often found directly beneath an impervious pavement.

Capillary moisture in soils located above the water table may be visualized as occurring in the following three zones:

- Capillary saturation.
- Partial capillary saturation.
- Contact moisture.

In the zone of capillary saturation, the soil is essentially saturated. The height of this zone depends not only on the soil but also on the history of the water table, since the height will be greater if the soil mass has been saturated previously.

The height of the zone of partial capillary saturation is likely to be considered greater than that of the zone of capillary saturation; it also depends on the water-table history. Its existence is the result of a few large voids serving effectively to stop capillary rise in some parts of the soil mass. Capillary water in this zone is still interconnected or "continuous," while the air voids may not be.

Above the zones of capillary and partial capillary saturation, water that percolates downward from the surface may be held in the soil by surface tension. It may fill the smaller voids or be present in the form of water films between the points of contact of the soil grains. Water may also be brought into this zone from the water table by evaporation and condensation. This moisture is termed "contact moisture."

One effect of contact moisture is apparent cohesion. An example of this is the behavior of sand on certain beaches. On these beaches, the dry sand located back from the edge of the water and above the height of capillary rise is generally dry and very loose and has little supporting power when unconfined. Closer to the water's edge, and particularly during periods of low tide, the sand is very firm and capable of supporting stationary or moving

automobiles and other vehicles. This apparent strength is due primarily to the existence of contact moisture left in the voids of the soil when the tide went out. The surface soil may be within the zone of partial or complete capillary saturation very close to the edge of the water. Somewhat similarly, capillary forces may be used to consolidate loose cohesionless deposits of very fine sands or silts in which the water table is at or near the ground surface. This consolidation is accomplished by lowering the water table by means of drains or well points. If the operation is properly carried out within the limits of the height of capillary rise, the soil above the lowered water table remains saturated by capillary moisture. The effect is to place the soil structure under capillary forces (such as tension in the water) that compress it. The soil may be compressed as effectively as though an equivalent external load had been placed on the surface of the soil mass.

Methods commonly used to control the detrimental effects of capillarity, particularly concerning roads and airport pavements, are mentioned briefly here. Additional attention is given to this subject in *Section II*, which is devoted to the closely allied subject of frost action.

As has been noted, if the water table is closer to the surface than the height of capillary rise, water will be brought up to the surface to replace water removed by evaporation. If evaporation is wholly or partially prevented, as by the construction of impervious pavement, water accumulates and may cause a reduction in shearing strength or cause swelling of the soil. This is true particularly when a fine-grained soil or a coarse soil that contains a detrimental amount of plastic fines is involved.

One obvious solution is to excavate the material that is subject to capillary action and replace it with a granular material. This is frequently quite expensive and usually may be justified only in areas where frost action is a factor.

Another approach is to include in the pavement structure a layer that is unaffected by capillary action. This is one of the functions of the base that is invariably used in flexible pavements. The base serves to interrupt the flow of capillary moisture, in addition to its other functions. Under certain circumstances, the base itself may have to be drained to ensure the removal of capillary water (see *Figure 7-2)*. This also is usually not justified unless other circumstances, such as frost action, are of importance.

Still another approach is to lower the water table, which may sometimes be accomplished by the use of side ditches. Subdrains may be installed for the same purpose (see *Figure 7-3, page 7-2)*. This approach is particularly effective in relatively pervious or free-draining soils. Some difficulty may be experienced in lowering the water table by this method in flat country because finding outlets for the drains is difficult. An alternative, used in many areas where the permanent water table is at or near the ground surface, is simply to build the highway or runway on a fill. Material that is not subject to detrimental capillarity is used to form a shallow fill. The bottom of the base is normally kept a minimum of 3 or 4 feet above the natural ground surface, depending on the soil used in the fill and other factors. A layer of sand, known as a sand blanket, or a geotextile fabric may be used to intercept capillary moisture, preventing its intrusion into the base course.

One Gradation of Filter Material

Minimum Distance 3'

Pavement

Turf

Base Course

Compacted Filter Material

Top of Subgrade

6"

Minimum 12"

6"

6" Drain Pipe

18"

Two Gradations of Filter Material

Minimum Distance 3'

Pavement

Turf

Base Course

Compacted Coarse Filter Material

Compacted Fine Filter Material

Top of Subgrade

6"

Minimum 12"

6"

2"

6" 18" 6"

6" Drain Pipe
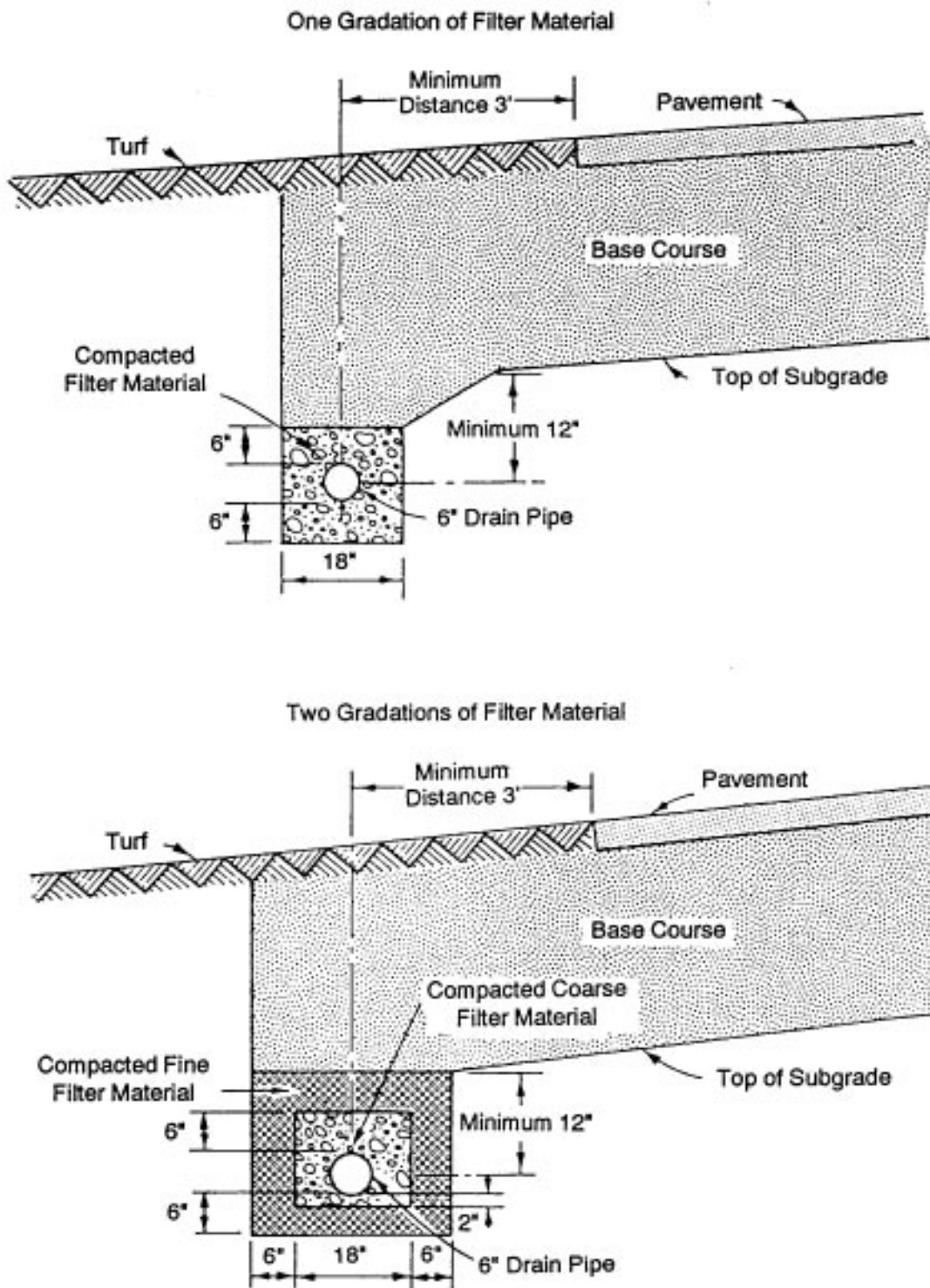
Figure 7-2. Base drains in an airfield pavement
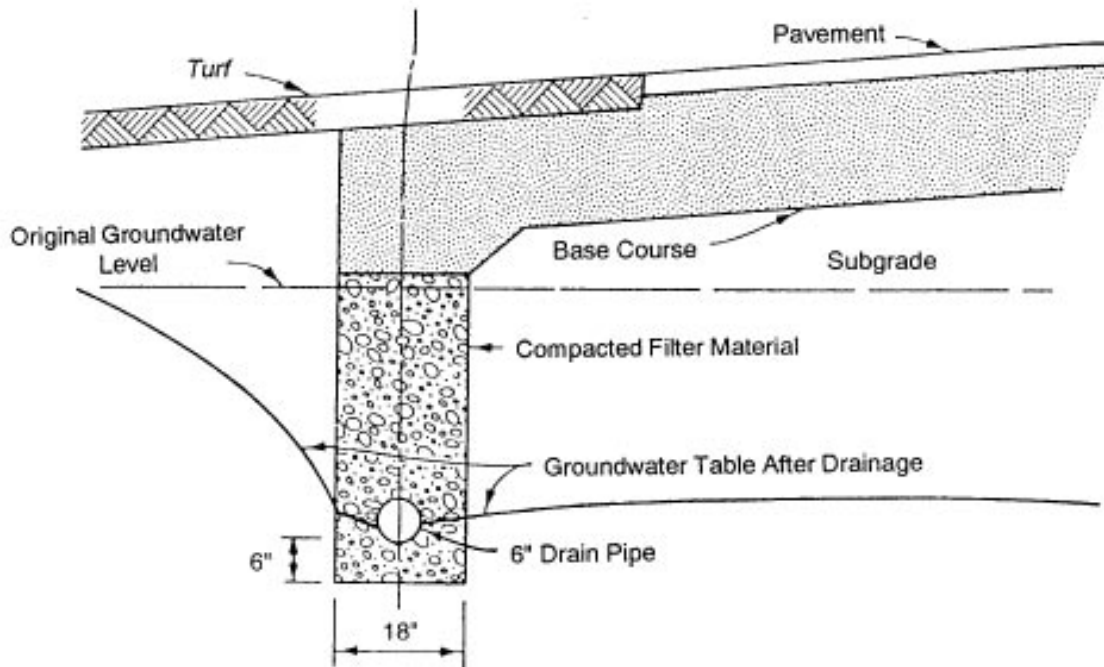
Figure 7-3. Typical subgrade drainage installation

Locating Groundwater Sources

Consider exploring rock aquifers only when soil aquifers are not present or when the soil aquifer cannot provide the required water supply. Identifying suitable well sites in rock aquifers is much more difficult than in soil aquifers. Also, water development is usually more time-consuming and costly and has a higher risk of failure. However, in some areas, rock aquifers are the only potential source of groundwater.

Hydrogeologic Indicators. Indicators that help identify groundwater sources are referred to as hydrogeologic indicators (*Table 7a*). They are divided into three major groups—reservoir, groundwater, and boundary. Groundwater indicators are those conditions or characteristics that directly or indirectly indicate groundwater occurrence. No indicator is 100 percent reliable, but the presence or absence of certain indicators or associations of indicators is fairly reliable.

Geologic Indicators. The type of rock or soil present is an important indicator because it usually defines the types of aquifers present and their water-producing characteristics. For field reconnaissance, the engineer need only recognize igneous, metamorphic, and sedimentary rocks and alluvium soil.

- Igneous rock. Usually a poor aquifer except where rock has been disturbed by faulting or fracturing. Igneous rock is normally incapable of storing or transmitting groundwater and acts as a barrier to groundwater flow.

- Metamorphic rock. Rarely capable of producing sufficient groundwater and has poor potential for groundwater development. Metamorphic rock is considered to be an effective barrier to groundwater flow.

- Sedimentary rock. Has the greatest capacity for holding groundwater. Unfractured sedimentary rock is capable of supplying low well yields,

Table 7a. Hydrogeologic indicators for groundwater exploration

Reservoir Indicators	Groundwater Indicators	Boundary Indicators
Rock type/geometry	Springs and seeps	Location of recharge areas
Stratigraphic sequence	Soil moisture	Location of discharge areas
Degree of lithification	Vegetation type	Impermeable barriers
Grain size	Vegetation density	Semipermeable barriers
Fracture density	Wetlands	Surface-water divides
Dissolution potential	Playas	
Cumulative structure density	Wells	
Drainage basin size	Reservoirs	
Drainage basin elevation and relief	Crop irrigation	
Drainage pattern	Salt encrustations	
Drainage density	Population distribution	
Landforms	Streams/rivers	
	Snow-melt patterns	
	Karst topography	

and fractured sedimentary rock is capable of supplying moderate to high well yields.

- Alluvium soil. Groundwater is most readily available in areas that are underlaid with alluvium. This is largely because uncemented or slightly cemented, compacted materials have maximum pore space and are relatively shallow and easily penetrated. The size of particles, the percentage of fines, and the degree of gradation have an important bearing on the yield of groundwater in soils. Clay yields almost no water; silt slowly yields some water, and well-sorted, clean, coarse sand and gravel freely yield water. Alluvial valleys are among the most productive terrains for recovering groundwater.

PERMEABILITY

Permeability is the property of soil that permits water to flow through it. Water may move through the continuous voids of a soil in much the same way as it moves through pipes and other conduits. As has been indicated, this movement of water through soils is frequently termed seepage and may also be called percolation. Soils vary greatly in their resistance to the flow of water through them. Relatively coarse soils, such as clean sands and gravels, offer comparatively little resistance to the flow of water; these are said to be permeable or pervious soils. Fine-grained soils, particularly clays, offer great resistance to the movement of water through them and are said to be relatively impermeable or impervious. Some water does move through these soils, however. The permeability of a soil reflects the ease with which it can be drained; therefore, soils are sometimes classed as well-drained, poorly drained, or impervious. Permeability is closely related to frost action and to the settlement of soils under load.

The term k is called the coefficient of permeability. It has units of velocity and may be regarded as the discharge velocity under a unit hydraulic gradient. The coefficient of permeability depends on the properties of the fluid involved and on the soil. Since water is the fluid normally involved in soil problems, and since its properties do not vary enough to affect most practical problems, the coefficient of permeability is regarded as a property of

the soil. Principal factors that determine the coefficient of permeability for a given soil include—

- Grain size.
- Void ratio.
- Structure.

The relationships among these different variables for typical soils are quite complex and preclude the development of formulas for the coefficient of permeability, except for the simplest cases. For the usual soil, k is determined experimentally, either in the laboratory or in the field. These methods are discussed briefly in the next paragraph. Typical values of the coefficient of permeability for the soil groups of the USCS are given in column 8 of *Table 5-4, page 5-15.*

DRAINAGE CHARACTERISTICS

The general drainage characteristics of soils classified under the USCS are given in column 12 of *Table 5-3, page 5-11.* Soils may be divided into three general groups on the basis of their drainage characteristics. They are—

- Well-drained.
- Poorly drained.
- Impervious.

Well-Drained Soils

Clean sands and gravels, such as those included in the (GW), (GP), (SW), or (SP) groups, fall into the classification of well-drained soils. These soils may be drained readily by gravity systems. In road and airfield construction, for example, open ditches may be used in these soils to intercept and carry away water that comes in from surrounding areas. This approach is very effective when used in combination with the sealing of the surface to reduce infiltration into the base or subgrade. In general, if the groundwater table around the site of a construction project is controlled in these soils, then it will be controlled under the site also.

Poorly Drained Soils

Poorly drained soils include inorganic and organic fine sands and silts, organic clays of low compressibility, and coarse-grained soils that contain an excess of nonplastic fines. Soils in the (ML), (OL), (MH), (GM), (GC), (SC), and (SM) groups, and many from the (Pt) group, generally fall into this category. Drainage by gravity alone is likely to be quite difficult for these soils.

Impervious Soils

Fine-grained, homogeneous, plastic soils and coarse-grained soils that contain plastic fines are considered impervious soils. This normally includes (CL) and (CH) soils and some in the (OH) groups. Subsurface drainage is so slow on these items that it is of little value in improving their condition. Any drainage process is apt to be difficult and expensive.

FILTER DESIGN

The selection of the proper filter material is of great importance since it largely determines the success or failure of the drainage system. A layer of filter material approximately 6 inches deep should be placed around all subsurface piping systems. The improper selection of a filter material can cause the drainage system to become inoperative in one of three ways:

- The pipe may become clogged by the infiltration of small soil particles.
- Particles in the protected soil may move into or through the filters, causing instability of the surface.
- Free groundwater may not be able to reach the pipe.

To prevent these failures from occurring, criteria have been developed based on the soil's gradation curve (see *Chapter 5*).

To prevent the clogging of a pipe by filter material moving through the perforations or openings, the following limiting requirements must be satisfied (see *Engineer Manual (EM) 1110-2-1901):*

- For slotted openings:

$$\frac{50 \text{ percent size of filter material}}{\text{slot width}} > 1.2$$

- For circular holes:

$$\frac{50 \text{ percent size of filter material}}{\text{hole diameter}} > 1$$

- For porous concrete pipes:

$$\frac{D_{85} \text{ filter (mm)}}{D_{15} \text{ aggregate (mm)}} > 5$$

- For woven filter cloths:

$$\frac{D_{85} \text{ surrounding soil}}{\text{Equivalent opening size (EOS) of cloth}} > 1$$

To prevent the movement of particles from the protected soil into or through the filters, the following conditions must be satisfied:

$$\frac{15 \text{ percent of filter material}}{85 \text{ percent size of protected soil}} < 5$$

and

$$\frac{50 \text{ percent size of filter material}}{50 \text{ percent size of protected soil}} < 25$$

To permit free water to reach the pipe, the filter material must be many times more pervious than the protected soil. This condition is fulfilled when the following requirement is met:

$$\frac{15 \text{ percent size of filter material}}{15 \text{ percent size of protected soil}} > 5$$

If it is not possible to obtain a mechanical analysis of available filter materials and protected soils, concrete sand with mechanical analysis limits as shown in *Figure 7-4,* may be used. Experience indicates that a well-graded concrete sand is satisfactory as a filter material in most sandy, silty soils.
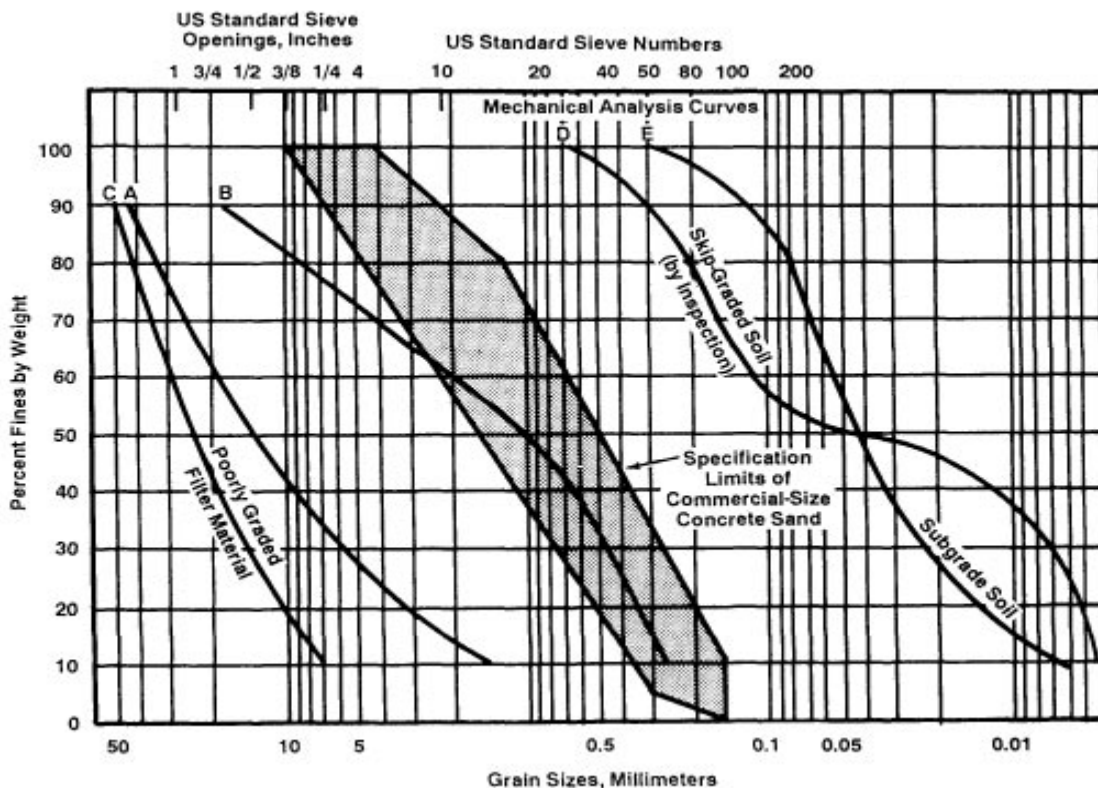
Figure 7-4. Mechanical analysis curves for filter material

POROSITY AND PERMEABILITY OF ROCKS

Porosity and permeability determine the water-bearing capability of a natural material.

Porosity

The amount of water that rocks can contain depends on the open spaces in therock. Porosity is the percentage of the total volume of the rock that is occupied by voids. Rock types vary greatly in size, number, and arrangement of their pore spaces and, consequently, in their ability to contain and yield water. The following list explains the porosity values of the types of rock displayed in *Figure 7-4a.*

- A and B—A decrease in porosity due to compaction.
- C—A natural sand with high porosity due to good sorting.
- D—A natural sand with low porosity due to poor sorting and a matrix of silt and clay.
- E—Low porosity due to segmentation.
- G—Porous zone between lava flows.
- H—Limestone made porous by solution along joints.
- I—Massive rock made porous by fracturing.
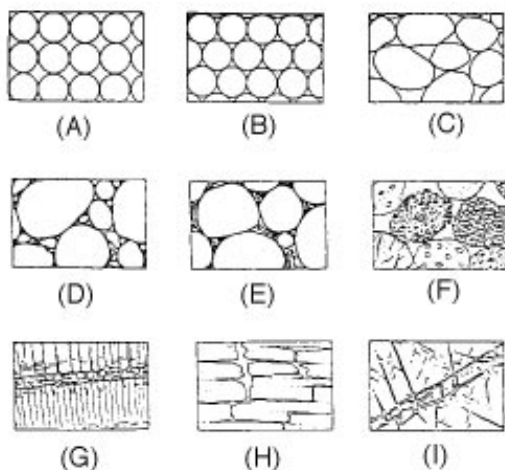
Figure 7-4a. Porosity in rocks

Permeability

The permeability of rock is its capacity for transmitting a fluid. The amount of permeability depends on the degree of porosity, the size and the shape of interconnections between pores, and the extent of the pore system.

WATER TABLE

In most regions, the depth that rocks are saturated with water depends largely on the permeability of the rocks, the amount of precipitation, and the topography. In permeable rocks, the surface below where the rocks are saturated is called the water table (*Figure 7b, page 7-1c*). The water table is—

- Not a level surface.
- Irregular and reflects the surface topography.
- Relatively high beneath hills.
- Closer to the surface or approaching the surface in valleys.

Perched Water Table

If impermeable layers are present, descending water stops at their upper surfaces. If a water table lies well below the surface, a mass of impermeable rock may intercept the descending water and hold it suspended above the normal saturated zone. This isolated, saturated zone then has its own water table. Wells drilled into this zone are poor quality, because the well could quickly be drained of its water supply.

Aquifer

An aquifer is a layer of rock below the water table. It is also called a water-bearing formation or a water-bearing stratum. Aquifers can be found in almost any area; however, they are difficult to locate in areas that do not have sedimentary rocks. Sands and sandstones usually constitute the best aquifers, but any rock with porosity and permeability can serve as a good water aquifer.

Saltwater Intrusion

There is always a danger of saltwater intrusion into groundwater sources along coastal areas and on islands. Because saltwater is unfit for most human needs, contamination can cause serious problems. When saltwater intrusion is discovered in the groundwater supply, determine the cause and mitigate it as soon as possible.

Section II. Frost Action

PROBLEMS

Frost action refers to any process that affects the ability of the soil to support a structure as a result of—

- Freezing.
- Thawing.

A difficult problem resulting from frost action is that pavements are frequently broken up or severely damaged as subgrades freeze during winter and thaw in the spring. In addition to the physical damage to pavements during freezing and thawing and the high cost of time, equipment, and personnel required in maintenance, the damage to communications routes or airfields may be great and, in some instances, intolerable strategically. In the spring or at other warm periods, thawing subgrades may become extremely unstable. In some severely affected areas, facilities have been closed to traffic until the subgrade recovered its stability.

The freezing index is a measure of the combined duration and magnitude of below-freezing temperature occurring during any given freezing season. *Figure 7-5, page 7-9,* shows the freezing index for a specific winter.

Freezing

Early theories attributed frost heaves to the expansion of water contained in soil voids upon freezing. However, this expansion would only be about 9 percent of the thickness of a frozen layer if caused by the water in the soil changing from the liquid to the solid state. It is not uncommon to note heaves as great as 60 percent; under laboratory conditions, heaves of as much as 300 percent have been recorded. These facts clearly indicate that heaving is due to the freezing of additional water that is attracted from the nonfrozen soil layers. Later studies have shown that frost heaves are primarily due to the growth of ice lenses in the soil at the plane of freezing temperatures.

The process of ice segregation may be pictured as follows: the thin layers of water adhering to soil grains become supercooled, meaning that this water remains liquid below 32 degrees Fahrenheit. A strong attraction exists between this water and the ice crystals that form in larger void spaces. This supercooled water flows by capillary action toward the already-formed crystals and freezes on contact. Continued crystal growth leads to the formation of an ice lens, which continues to grow in thickness and width until the source of water is cut off or the temperature rises above the normal freezing point (see *Figure 7-6, page 7-10*).

Thawing

The second phase of frost damage occurs toward the end of winter or in early spring when thawing begins. The frozen subgrade thaws both from the top and the bottom. For the latter case, if the air temperature remains barely below the freezing point for a sufficient length of time, deeply frozen soils gradually thaw from the bottom upward because of the outward conduction of heat from the earth's interior. An insulating blanket of snow ends to encourage this type of thawing. From an engineering standpoint, this

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ADM   area defense management

alidade In plane tabling, a straight edge having a telescopic sight or other means of sighting parallel to it.

aquifer Any geologic formation containing water.

artesian Refers to ground water confined under hydrostatic pressure.

ASCS   Agricultural Stabilization and Conservation Service

attitude The position of a structural surface relative to the horizontal and expressed by the strike and dip.

bedrock The lowest level of unbroken, solid rock. It is overlaid in most places by soil or rock fragments.

borings The chips, fragments, or dust produced in drilling or driving a hole into the earth's surface.

bpi   bits per inch

cobble A rock fragment larger than a pebble and smaller than a boulder (64 to 256 millimeters in diameter) that is somewhat rounded or otherwise modified by abrasion in the course of transport.

conglomerates Rocks composed of rounded fragments, varying from small pebbles to large boulders, and held together by a natural cement.

contour line A line connecting points of equal elevation above or below a datum plane.

CP   command post

DC   District of Columbia

DIA   Defense Intelligence Agency

EROS   Earth Resources Observation System

ERTS   Early Remote Tracking System

fluvial Pertaining to rivers and streams.

geology The science that deals with the physical history of the earth, rocks that compose the earth, and the physical changes that the earth has undergone or is undergoing.

geomorphology The origin and development of the topography of the continents.

geophysical exploration Locating and studying underground deposits of ores, mineral, oil, gas, and water.

geosyncline A downward trough of the earth's crust where sediment accumulates.

HCl   hydrochloric

hydrogeologic Refers to geologic features that may indicate the presence of water.

hydrologic cycle A cycle in which water is evaporated from the sea, then precipitated from the atmosphere to the surface of the land, and finally returned to the sea by rivers and streams.

IR   infrared

LANDSAT   land satellite

leaching The process where the more soluble compounds are removed by percolating groundwater.

lithification Conversion of unconsolidated sediments into solid rock.

m   meter(s)

MSS   Multispectral Scanner System

photogeology The art and science of using photo images to determine the geology of an area.

plane table A drawing board mounted on a tripod. It is used in the field for obtaining and plotting survey data.

PO   post office

porosity. The state or quality of being porous, expressed as a percentage of the volume of the pores of a rock to the total volume of its mass.

rhyolite A fine-grained igneous rock that is rich in silica. The volcanic equivalent of granite.

schist Metamorphic crystalline rock having a closely foliated structure that allows division along approximately parallel planes. A fine- to coarse-grained rock that is composed of discontinuous thin layers of parallel mica, chlorite, hornblende, or other crystals.

SD   South Dakota

SLAR   side-looking radar

stratigraphic sequence The classification, correlation, and interpretation of stratified rocks.

topography The relief features or surface configurations of an area.

USGS   United States Geological Survey

UT   Utah

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