**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.
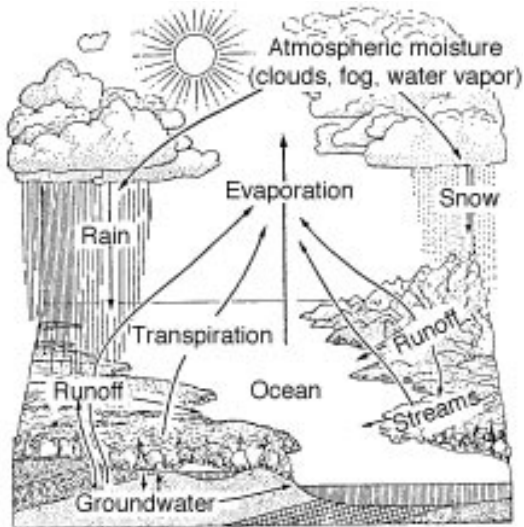


**Figure 7a. Hydrologic cycle**

## 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.
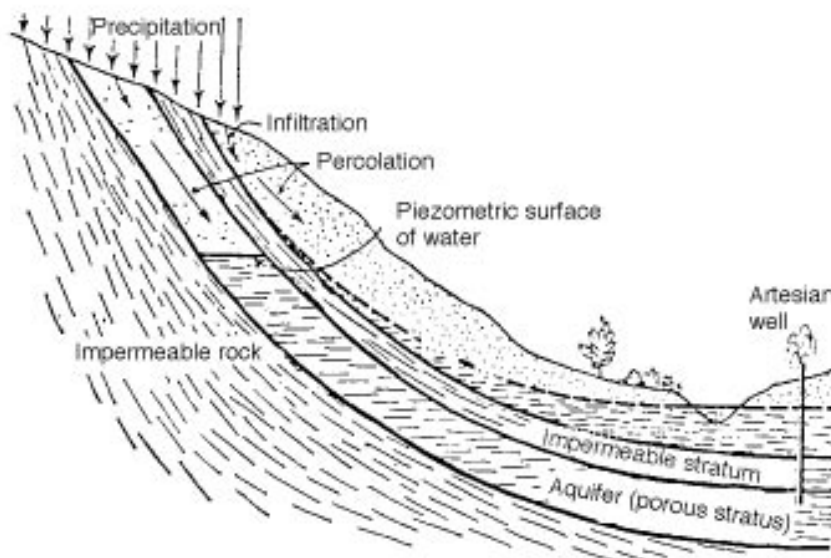
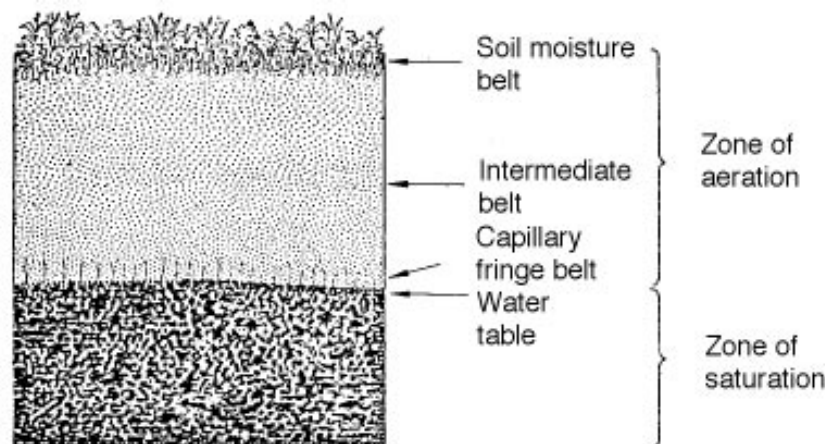

**Figure 7b. Artesian groundwater**

**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.
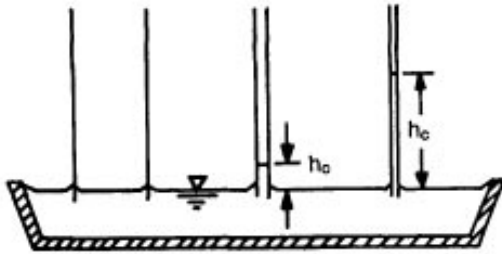


**Figure 7-1. Capillary rise of moisture**

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.
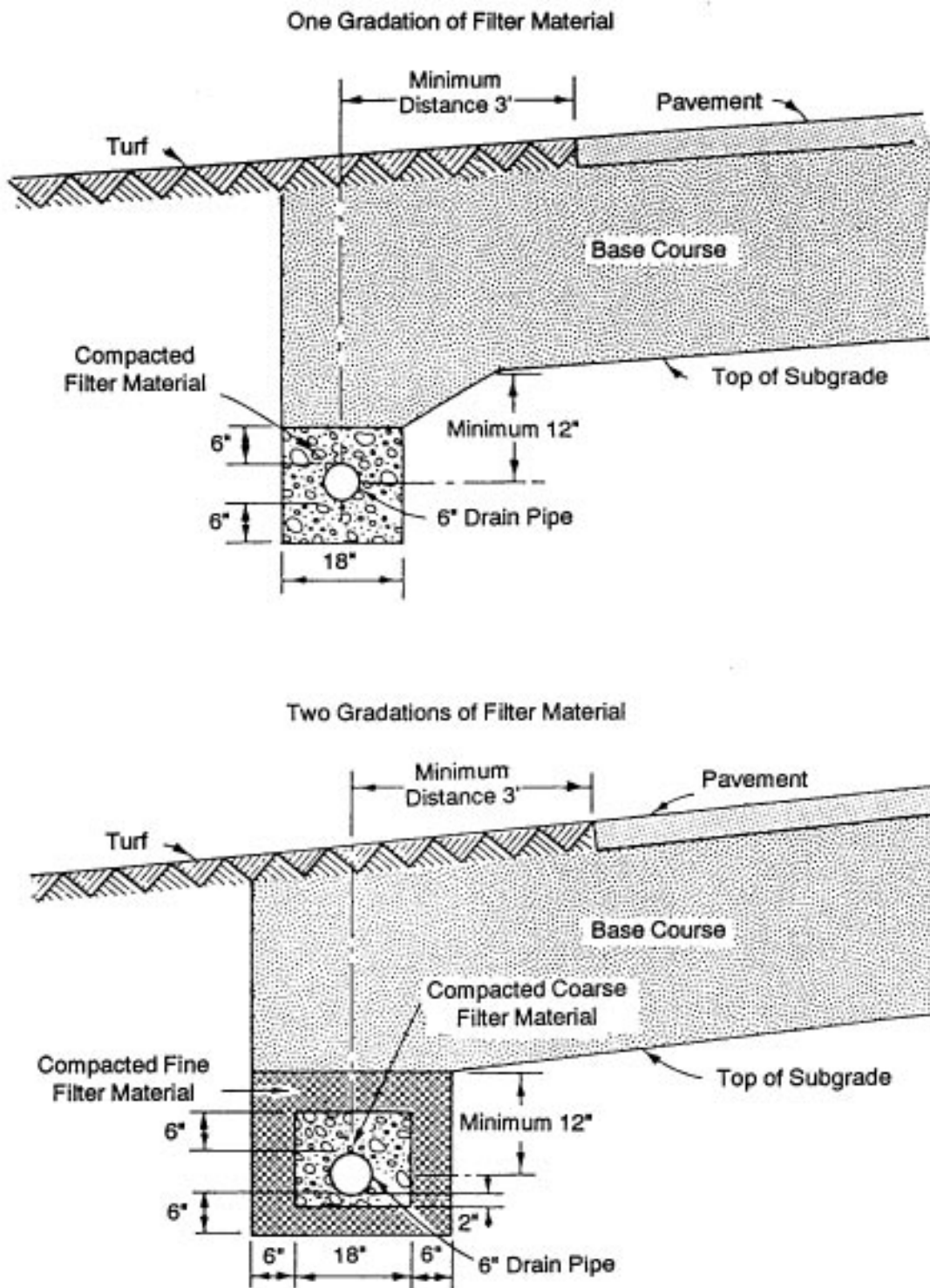
One Gradation of Filter Material

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

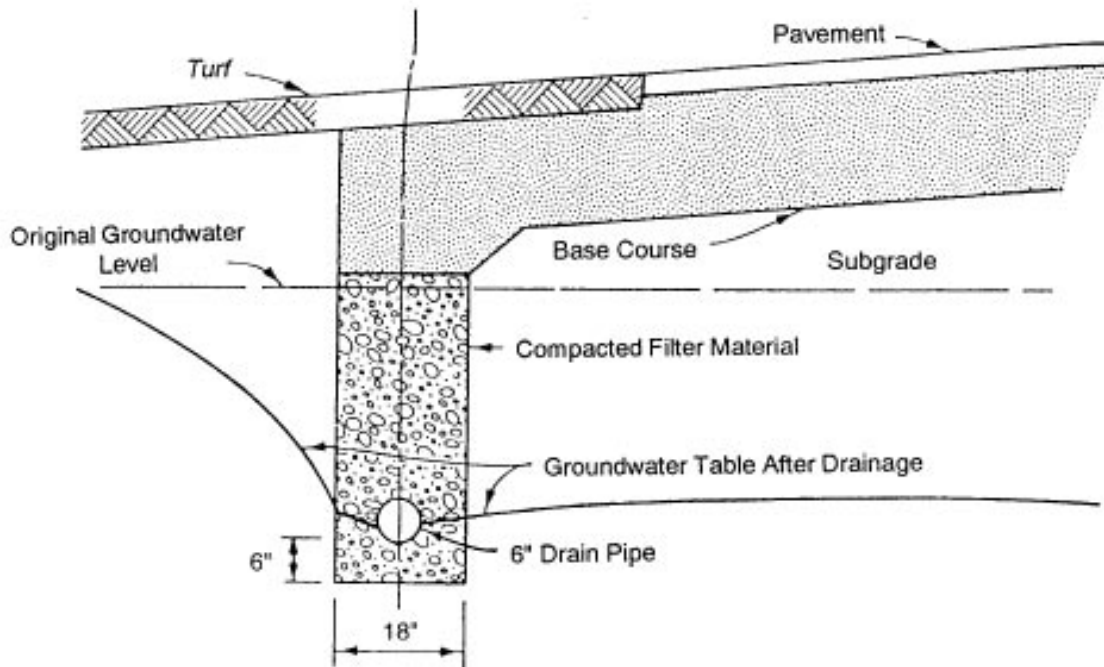**Figure 7-2.  Base drains in an airfield pavement**

**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:

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

- For circular holes:

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

- 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:

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

and

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

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:

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

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.
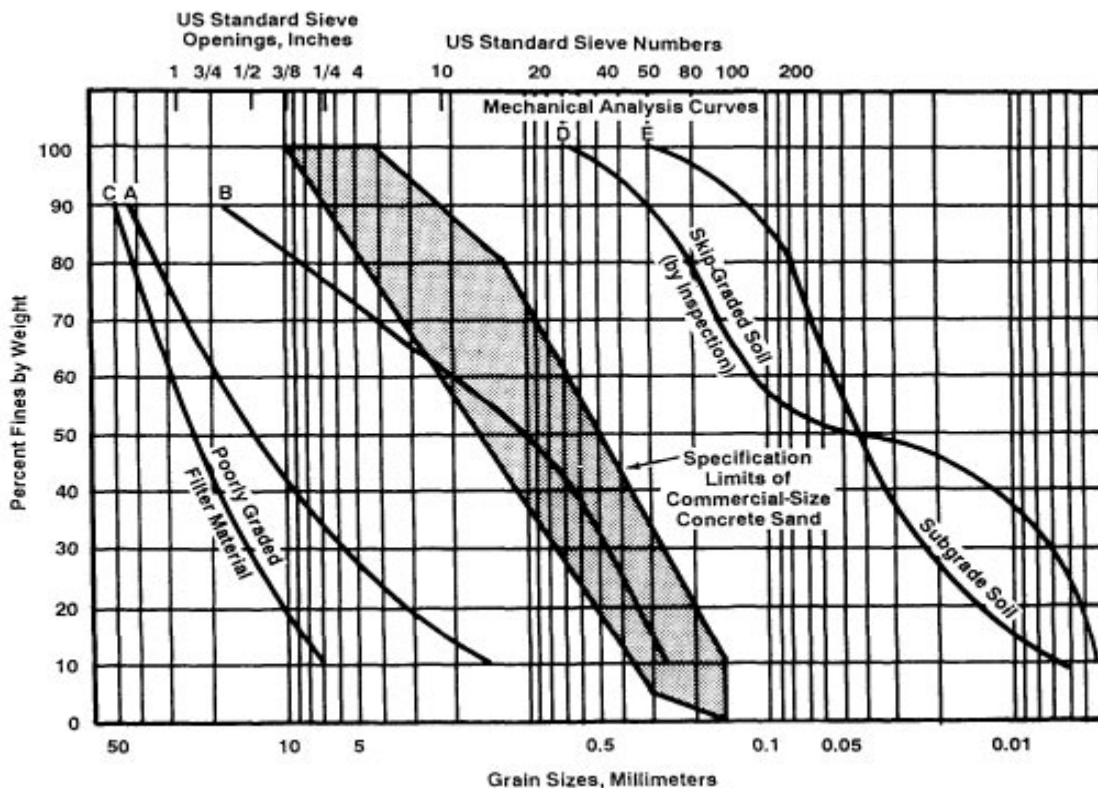


**Figure 7-4. Mechanical analysis curves for filter material**

## 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.
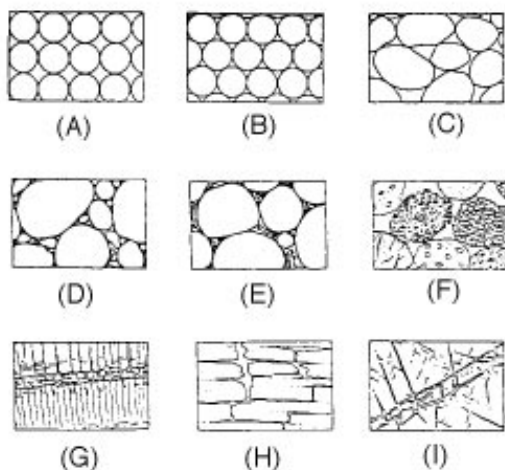- I—Massive rock made porous by fracturing.



**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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