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

SOURCES OF WATER

Water in the soil maybe from a surface or a subsurface source.

Surface Water

Water enters through soil surfaces unless measures are taken to seal the surface to prevent entry. Even sealed surfaces may have cracks, joints, or fissures that admit water. In concrete pavement, for instance, the contraction and expansion joints are points of entry for water. After the pavement has been subjected to many cycies of expansion and contraction, the joint filler may be imperfect, thereby allowing water to seep into the base course or subgrade.

Surface water may also enter from the sides of the road or airfield, even though the surface itself is entirely adequate. To reduce this effect, shoulders and ditches are sloped to carry the water away at an acceptable rate. If adequate maintenance is not provided throughout the life of the facility, vegetation or sedimentation may reduce the efficiency of the drainage so that water will frequently stand in the drainage ditch. This water may then be absorbed by the base and subgrade.

Subsurface Water

Subsurface moisture in soils may come from one of the following sources:

- Free, or gravitional, water (controlled by the force of gravity).
- Hydroscopic moisture (controlled by forces of absorption).
- Capillary moisture (controlled by forces of capillarity).

Free, or Gravitational, Water. Water that percolates down from the surface eventually reaches a depth at which 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.

Hydroscopic Moisture. When wet soil is air-dried, moisture is removed by evaporation until the hydroscopic 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 hydroscopic moisture content. Hydroscopic 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.

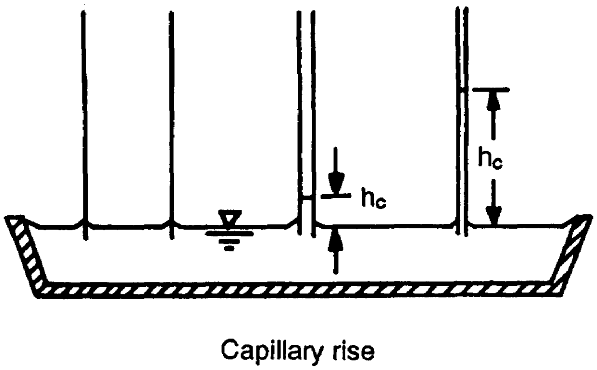

Figure 7-1. Capillary rise of moisture.

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 maybe installed for the same purpose (see *Figure 7-3, page 7-6)*. 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.

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 maybe 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, fail into the classification of well-drained soils. These soils may be drained readily by gravity systems. In road and

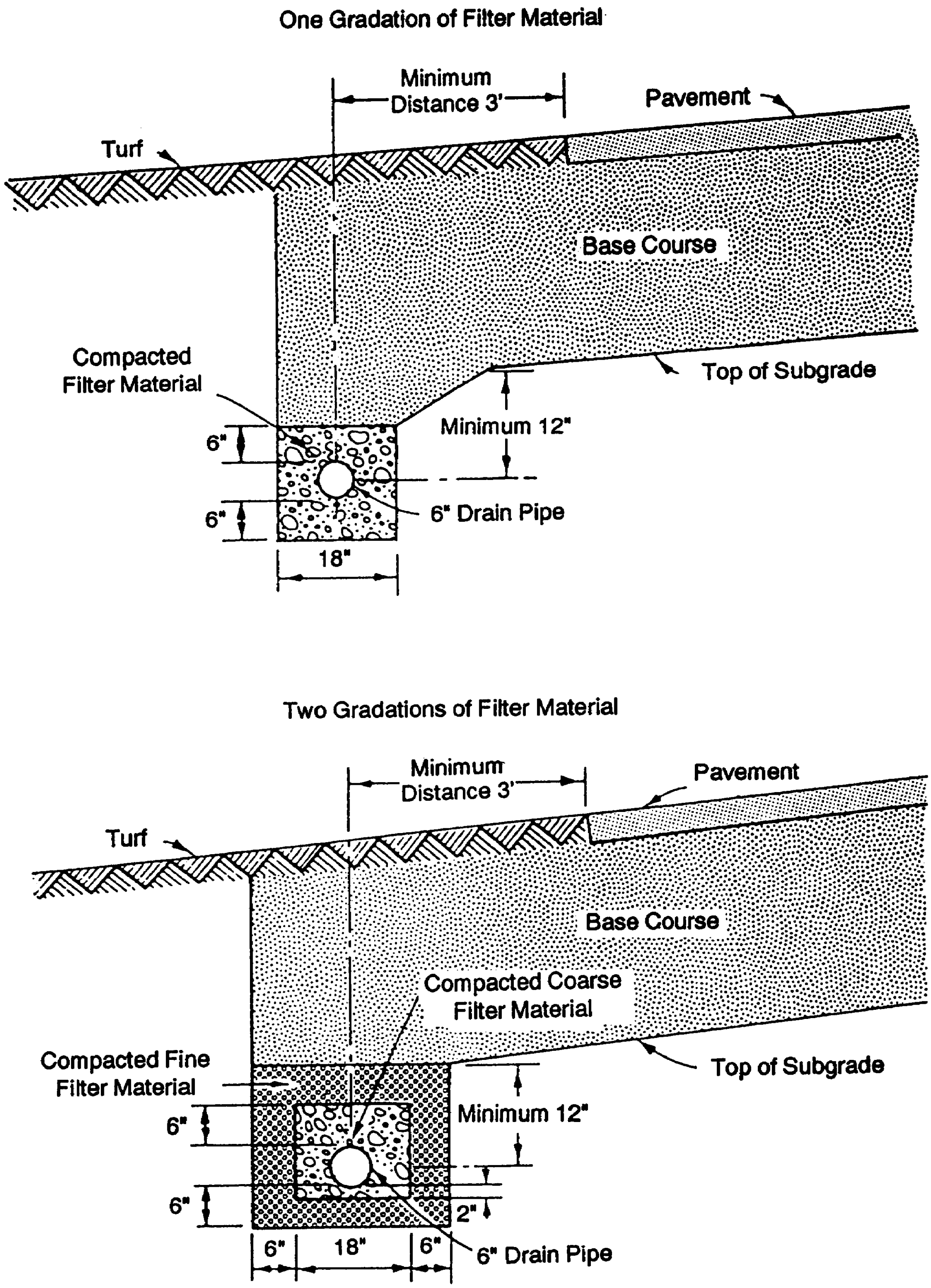

Figure 7-2. Base drains in an airfield pavement.

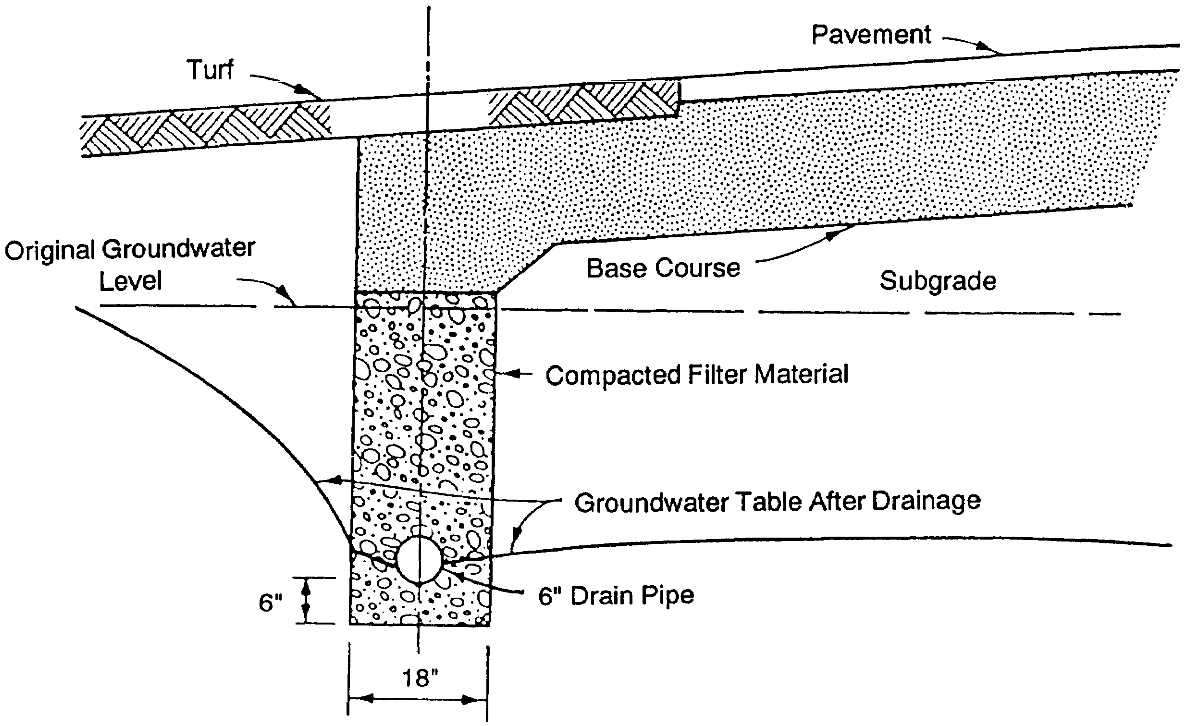

Figure 7-3. Typical subgrade drainage installation.

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, page 7-8,* may be used. Experience indicates that a well-graded concrete sand is satisfactory as a filter material in most sandy, silty soils.

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

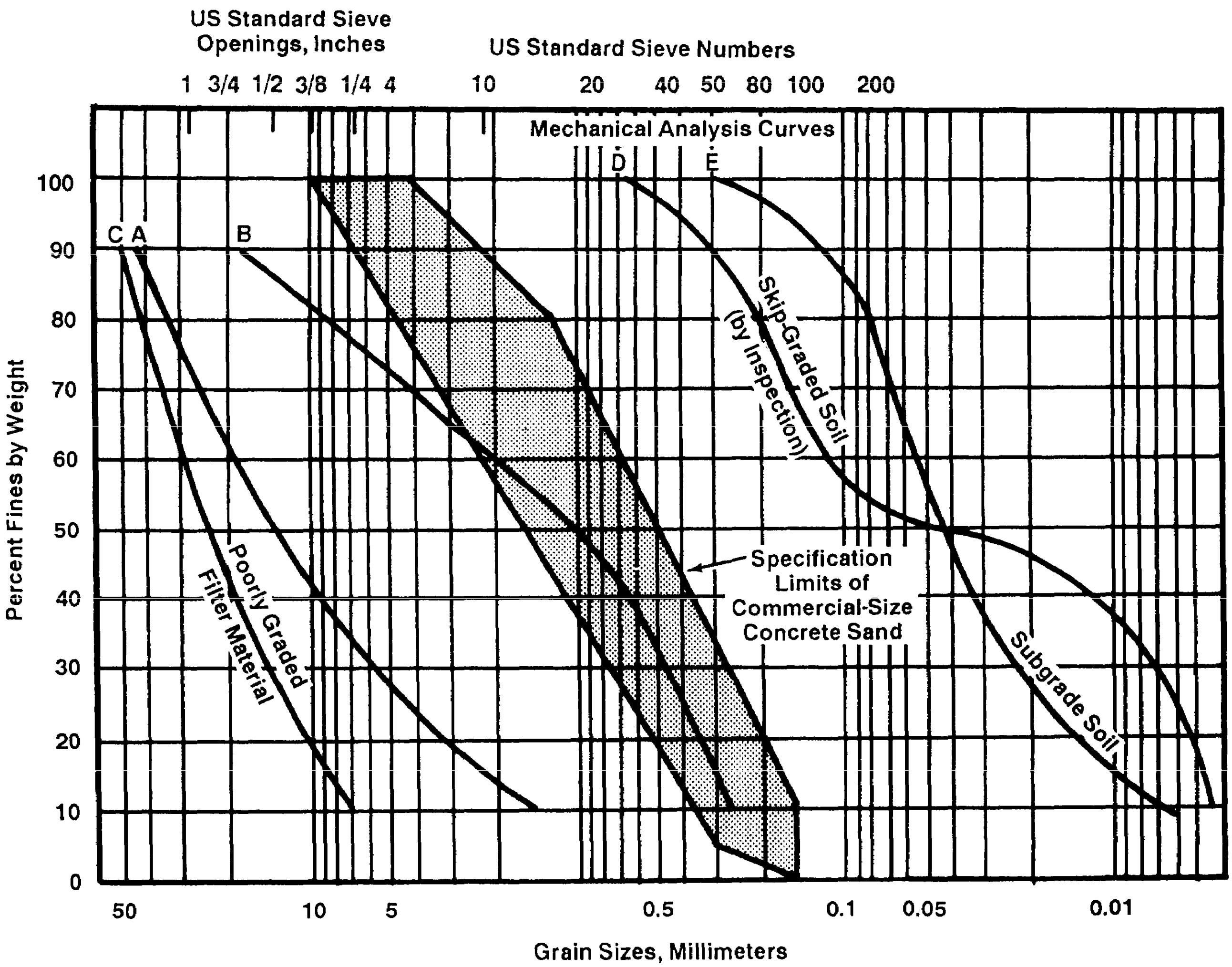

Figure 7-4. Mechanical analysis curves for filter material.

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 tends to encourage this type of thawing. From an engineering standpoint, this

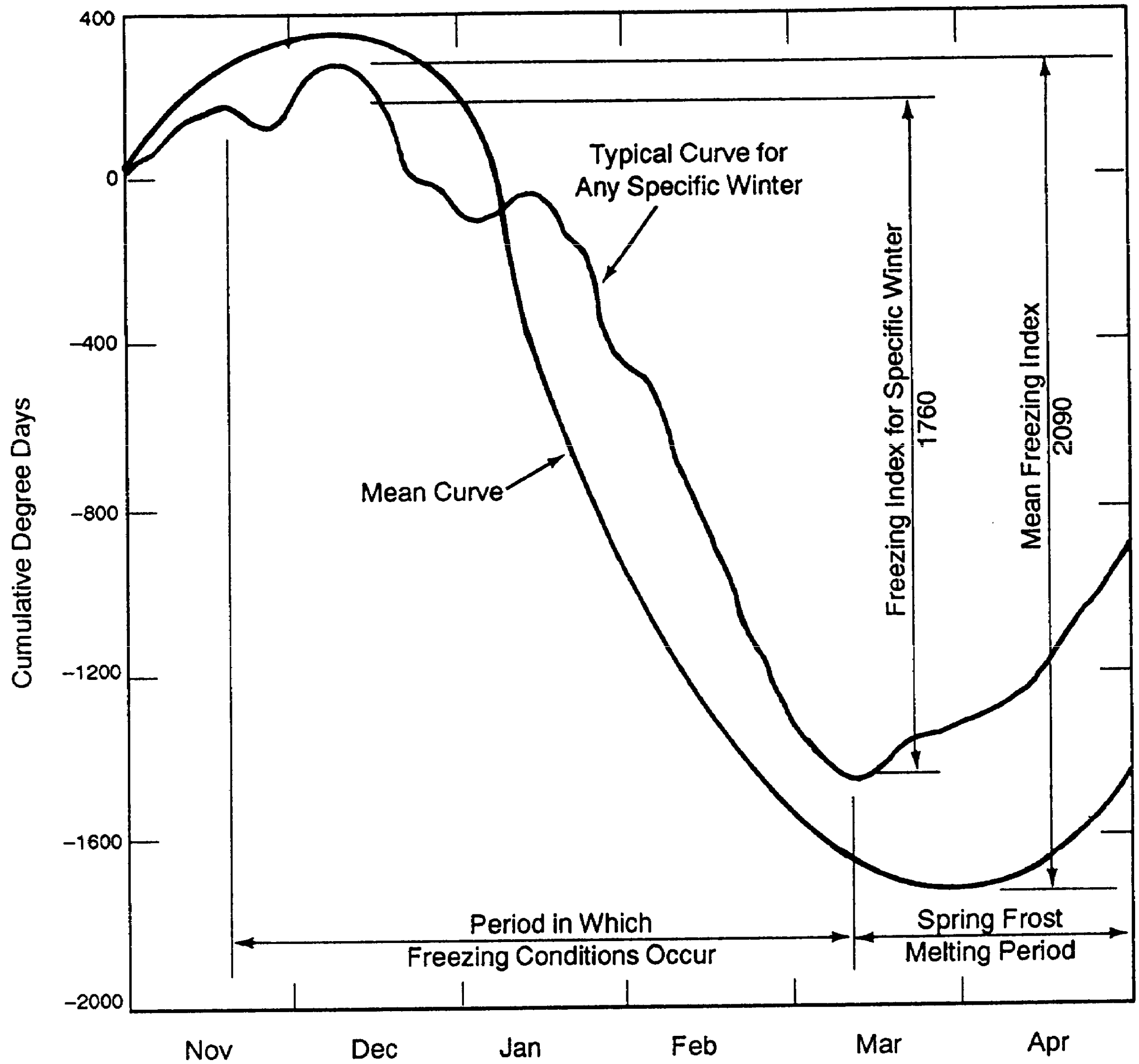

Figure 7-5. Determination of freezing index.

thawing condition is desirable, because it permits melted water from thawed ice lenses to seep back through the lower soil layers to the water table from which it was drawn during the freezing process. Such dissipation of the melted water places no load on the surface drainage system, and no tendency exists to reduce subgrade stability by reason of saturation. Therefore, there is little difficulty in maintaining unpaved roads in a passable condition.

Thawing occurs from the top downward if the surface temperature rises from below the freezing point to well above that point and remains there for an appreciable time. This leaves a frozen layer beneath the thawed subgrade. The thawed soil between the pavement and this frozen layer contains an excessive amount of moisture resulting from the melting of the ice it contained. Since the frozen soil layer is impervious to the water, adequate drainage is almost impossible. The poor stability of the resulting supersaturated road or airfield subgrade accounts for many pavement failures. Unsurfaced earthen roads may become impassable when supersaturated.

Thawing from both the top and bottom occurs when the air temperature remains barely above the freezing point for a sufficient

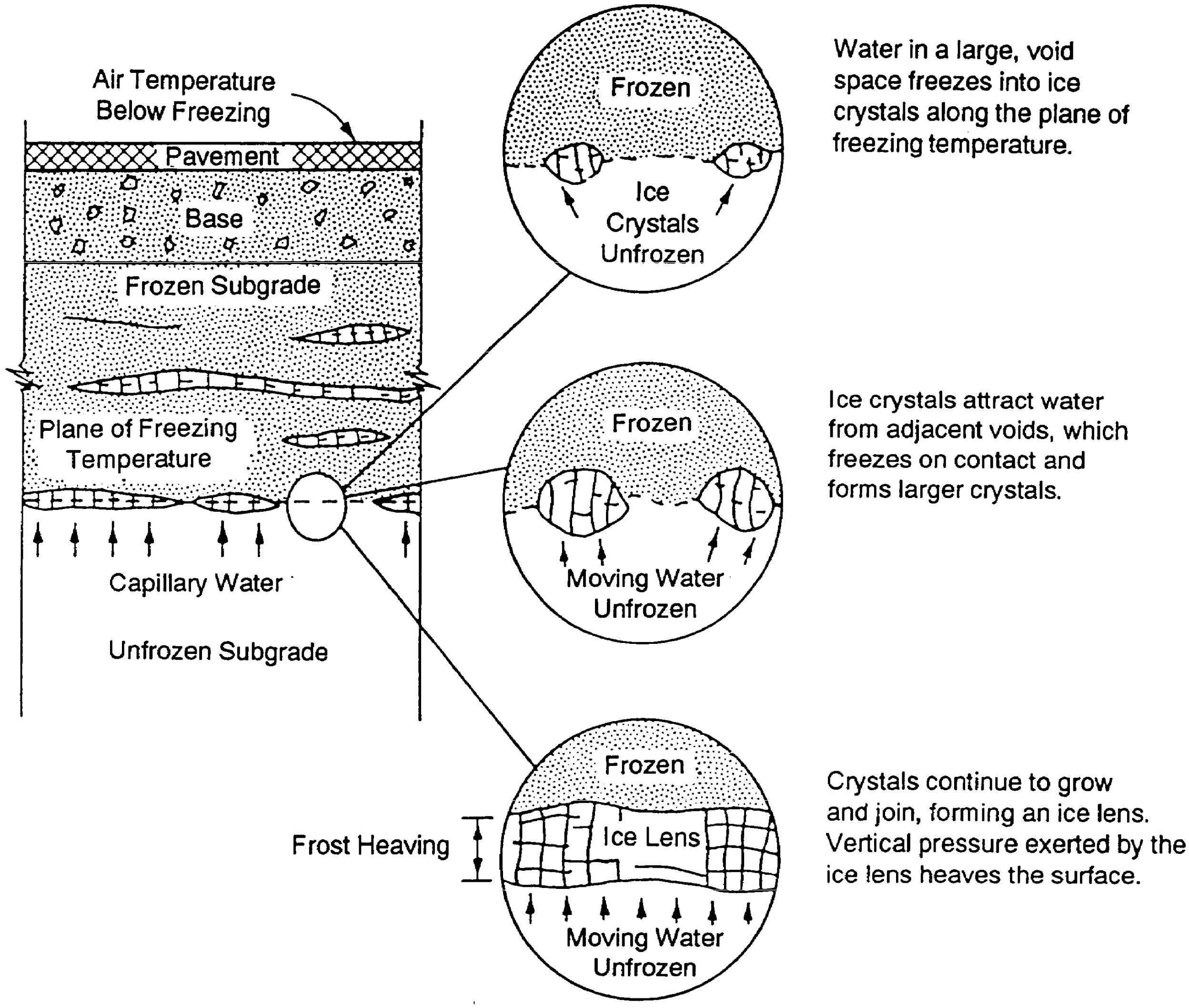

Figure 7-6. Formation of ice crystals on frost line.

time. Such thawing results in reduced soil stability, the duration of which would be less than for soil where the thaw is only from the top downward.

CONDITIONS

Temperatures below 32 degrees Fahrenhiet must penetrate the soil to cause freezing. In general, the thickness of ice layers (and the amount of consequent heaving) is inversely proportional to the rate of penetration of freezing temperature into the soil. Thus, winters with fluctuating air temperatures at the beginning of the freezing season produce more damaging heaves than extremely cold, harsh winters where the water is more likely to be frozen in place before ice segregation can take place.

A source of water must be available to promote the accumulation of ice lenses. Water may come from—

- A high groundwater table.
- A capillary supply from an adjoining water table.
- Infiltration at the surface.
- A water-bearing system (aquifer).
- Voids of fine-grained soils.

Ice segregation usually occurs in soils when a favorable source of water and freezing tern peratures are present. The potential intensity of ice segregation in a soil depends largely on the size of the void space and may be expressed as an empirical fuction of grain size.

Inorganic soils containing 3 percent or more by weight of grains finer than 0.02 mm in diameter are generally considered frost susceptible. Although soils may have as high as 10 percent by weight of grains finer than 0.02 mm without being frost susceptible, the tendency of these soils to occur interbedded with other soils makes it impractical to consider them separately.

Frost-susceptible soils are classified in the following groups:

- F-1.
- F-2.
- F-3.
- F-4.

They are listed approximately in the order of increasing susceptibility to frost heaving or weakening as a result of frost melting (see *Table 7-1)*. The order of listing of subgroups under groups F-3 and F-4 does not necessarily indicate the order of susceptibility to frost heaving or weakening of these subgroups. There is some overlapping of frost susceptibility between groups. The soils in group F-4 are of especially high frost susceptibility. Soil names are defined in the USCS.

Varved clays consist of alternating layers of medium-gray inorganic silt and darker silty clay. The thickness of the layers rarely exceeds 1/2 inch, but occasionally much thicker varves are encountered. They are likely to combine the undesirable properties of both silts and soft clays. Varved clays are likely to soften more readily than homogeneous clays with equal water content. However, local experience and conditions should be taken into account since, under favorable conditions (as when insufficient moisture is available for significant ice segregation), little or no detrimental frost action may occur. Some evidence exists that pavements in the seasonal frost zone, constructed on varved clay subgrades in which the deposit and

Table 7-1. Frost-susceptible soil groups.

Frost Group	Kind of Soil	Percentage Finer Than 0.02 mm by Weight	Typical Soil Types Under Unified Soil Classification System
F-1	Gravelly soils	6 to 10	GM, GW-GM, GP-GM
F-2	Gravelly soils	10 to 20	GM, GW-GM, GP-GM
	Sands	6 to 15	SM, SW-SM, SP-SM
F-3	Gravelly soils	Over 20	GM, GC
	Sands, except very fine silty sands	Over 15	SM, SC
	Clays, PI > 12	—	CL, CH
F-4	All silts	—	ML, MH
	Very fine silty sands	Over 15	SM
	Clays, PI > 12	—	CL, CL-ML
	Varved clays and other fine-grained, banded sediments	—	CL and ML; CL, ML; and SM; CL, CH, and ML; CL, CH, ML, and SM

depth to groundwater are relatively uniform, have performed satisfactorily. Where subgrade conditions are uniform and local evidence indicates that the degree of heave is not exceptional, the varved clay subgrade soil should be assigned a group F-4 frost-susceptibility classification.

EFFECTS

Frost action can cause severe damage to roads and airfields. The problems include heaving and the resultant loss of pavement strength.

Heaving

Frost heave, indicated by the raising of the pavement, is directly associated with ice segregation and is visible evidence on the surface that ice lenses have formed in the subgrade material. Heave may be uniform or nonuniform, depending on variations in the character of the soils and the groundwater conditions underlying the pavement.

The tendency of the ice layers to develop and grow increases rapidly with decreasing grain size. On the other hand, the rate at which the water flows in an open system toward the zone of freezing decreases with decreasing grain size. Therefore, it is reasonable to expect that the worst frost heave conditions would be encountered in soils having an intermediate grain size. Silt soils, silty sands, and silty gravels tend to exhibit the greatest frost heave.

Uniform heave is the raising of adjacent areas of pavement surface by approximately equal amounts. In this type of heave, the initial shape and smoothness of the surface remains substantially unchanged. When nonuniform heave occurs, the heave of adjacent areas is appreciably different, resulting in objectionable unevenness or abrupt changes in the grade at the pavement surface.

Conditions conducive to uniform heave may exist, for example, in a section of pavement constructed with a fairly uniform stripping or fill depth, uniform depth to groundwater table, and uniform soil characteristics. Conditions conducive to irregular heave occur typically at locations where subgrades vary between clean sand and silty soils or at abrupt transitions from cut to fill sections with groundwater close to the surface.

Lateral drains, culverts, or utility lines placed under pavements on frost-susceptible subgrades frequently cause abrupt differential heaving. Wherever possible, such facilities should not be placed beneath these pavements, or transitions should be provided so as to moderate the roughening of the pavement during the period of heave.

Loss of Pavement Strength

When ice segregation occurs in a frost-susceptible soil, the soil's strength is reduced as is the load-supporting capacity of the pavement during prolonged frost-melting periods. This often occurs during winter and spring thawing periods, because near-surface ice melts and water from melting snow or rain may infiltrate through the surface causing an excess of water. This water cannot drain through the still-frozen soil below, or through the shoulders, or redistribute itself readily. The soil is thus softened.

Supporting capacity may be reduced in clay subgrades even through significant heave has not occurred. This may occur because water for ice segregation is extracted from the clay lattice below, and the resulting shrinkage of the lattice largely balances the volume of the ice lenses formed.

Further, traffic may cause remolding or develop hydrostatic pressure within the pores of the soil during the period of weakening, thus resulting in further-reduced subgrade strength. The degree to which a soil loses strength during a frost-melting period and the length of the period during which the strength of the soil is reduced depend on—

- The type of soil.
- Temperature conditions during freezing and thawing periods,

- The amount and type of traffic during the frost-melting periods.
- The availability of water during the freezing and thawing periods.
- Drainage conditions.

Rigid Pavements (Concrete). Concrete alone has only a little tensile strength, and a slab is designed to resist loads from above while receiving uniform support from the subgrade and base course. Therefore, slabs have a tendency to break up as a result of the upthrust from nonuniform heaving soils causing a point bearing. As a rule, if rigid pavements survive the ill effects of upheaval, they will generally not fail during thawing. Reinforced concrete will carry a load by beam action over a sub grade having either frozen or supersaturated areas. Rigid pavements will carry a load over subgrades that are both frozen and supersaturated. The capacity to bear the design load is reduced, however, when the rigid slab is supported entirely by supersaturated, semiliquid subgrades.

Flexible Bituminous Pavements. The ductility of flexible pavements helps them to deflect with heaving and later resume their original positions. While heaving may produce severe bumps and cracks, usually it is not too serious for flexible pavements. By contrast, a load applied to poorly supported pavements during the thawing period normally results in rapid failure.

Slopes. Exposed back slopes and side slopes of cuts and fills in fine-g-rained soil have a tendency to slough off during the thawing process. The additional weight of water plus the soil exceeds the shearing strength of the soil, and the hydrostatic head of water exerts the greatest pressure at the foot of the slope. This causes sloughing at the toe of the slope, which multiplies the failure by consecutive shear failures due to inadequate stability of the altered slopes. Flatter slopes reduce this problem. Sustained traffic over severely weakened areas afflicted with frost boils initiates a pumping action that results in complete pavement failure in the immediate vicinity.

INVESTIGATIONAL PROCEDURES

The field and laboratory investigations conducted according to *Chapter 5* of this manual usually provide sufficient information to determine whether a given combination of soil and water conditions beneath the pavement are conducive to frost action. This procedure for determining whether the conditions necessary for ice segregation are present at a proposed site are discussed in the following paragraphs. As stated earlier in this chapter, inorganic soils containing 3 percent or more by weight of grains finer than 0.02 mm are generally considered susceptible to ice segregation. Thus, examination of the fine portion of the gradation curve obtained from hydrometer analysis or the recantation process for these materials indicates whether they should be assumed frost susceptible. In borderline cases, or where unusual materials are involved, slow laboratory freezing tests may be performed to measure the relative frost susceptibility.

The freezing index value should be computed from actual daily air temperatures, if possible. Obtain the air temperatures from a weather station located as close as possible to the construction site. Differences in elevations, topographical positions, and nearness of cities, bodies of water, or other sources of heat may cause considerable variations in freezing indexes over short distances. These variations are of greater importance to the design in areas of a mean design freezing index of less than 100 (that is, a design freezing index of less than 500) than they are farther north.

The depth to which freezing temperatures penetrate below the surface of a pavement depends principally on the magnitude and duration of below-freezing air temperatures and on the amount of water present in the base, subbase, and subgrade.

A potentially troublesome water supply for ice segregation is present if the highest groundwater at any time of the year is within 5 feet of the proposed subgrade surface or the top of any frost-susceptible base materials. When the depth to the uppermost water table is in excess of 10 feet throughout the year, a source of water for substantial ice segregation is usually not present unless the soil contains a significant percentage of silt. In homogeneous clay soils, the water content that the clay subgrade will attain under a pavement is usually sufficient to provide water for some ice segregation even with a remote water table. Water may also enter a frost-susceptible subgrade by surface infiltration through pavement areas. *Figure 7-7* illustrates sources of water that feed growing ice lenses, causing frost action.

CONTROL

An engineer cannot prevent the temperatures that cause frost action. If a road or runway is constructed in a climate where freezing temperatures occur in winter, in all probability the soil beneath the pavement will freeze unless the period of lowered temperatures is very short. However, several construction techniques may be applied to counteract the presence of water and frost-susceptible soils.

Every effort should be made to lower the groundwater table in relation to the grade of the road or runway. This may be accomplished by installing subsurface drains or open side ditches, provided suitable outlets are available and that the subgrade soil is drainable. The same result maybe achieved by raising the grade line in relation to the water table. Whatever means are employed for producing the condition, the distance from the top of the proposed subgrade surface (or any frost-susceptible base material used) to the highest probably elevation of the water table should not be less than 5 feet. Distances greater than this are very desirable if they can be obtained at a reasonable cost.

Where it is possible, upward water movement should be prevented, In many cases, lowering the water table may not be practical. An example is in swampy areas where an outlets for subsurface drains might not be present. One method of preventing the rise of water would be to place a 6-inch layer of pervious, coarse-grained soil 2 or 3 feet beneath the surface. This layer would be designed as a filter to prevent clogging the pores with finer material, which would defeat the original purpose. If the depth of frost penetration is not too great, it maybe less expensive to backfill completely with granular material. Another successful method, though expensive, is to excavate to the frost line and backfill with granular material. In some cases, soil cement and asphalt-stabilized mixtures 6 inches thick have been used effectively to cut off the upward movement of water.

Even though the site selected may be on ideal soil, invariably on long stretches of roads or on wide expanses of runways, localized areas will be subject to frost action. These areas should be removed and replaced with select granular material. Unless this is meticulously carried out, differential heaving during freezing and severe strength loss upon thawing, may result.

The most generally accepted method of preventing subgrade failure due to frost action is to provide a suitable insulating cover to keep freezing temperatures from penetrating the subgrade to a significant depth. This insulating cover consists of a suitable thick pavement and a thick nonfrost-susceptible base course.

If the wearing surface is cleared of snow during freezing weather, the shoulders should also be kept free of snow. Where this is not the case, freezing will set in first beneath the wearing surface. This permits water to be drawn into and accumulate in the subgrade from the unfrozen shoulder area, which is protected by the insulating snow. If both areas are free of snow, then freezing will begin in the shoulder area because it is not protected by a pavement. Under this condition, water is drawn from the subgrade to the shoulder area. As freezing progresses to include the subgrade, there will be little frost action unless more water is available from groundwater or seepage.

Base Composition Requirements

All base and subbase course materials lying within design depth of frost penetration

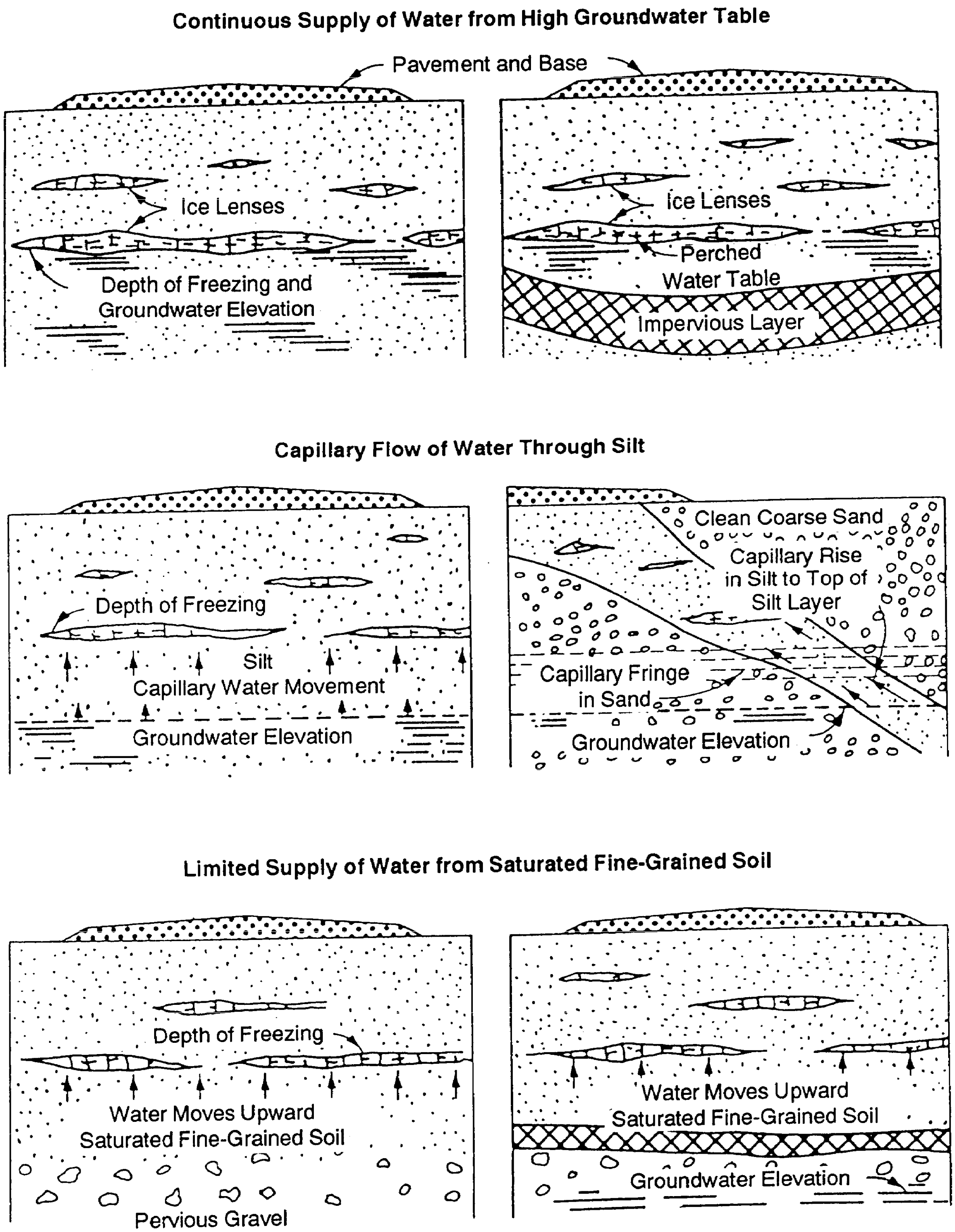

Figure 7-7. Sources of water that feed growing ice lenses.

should be nonfrost-susceptible. Where the combined thickness of pavement and base or-subbase over a frost-susceptible subgrade is less than the design depth of frost penetration, the following additional design requirements apply.

For both flexible and rigid pavements, the bottom 4 inches of base or subbase in contact with the subgrade, as a minimum, will consist of any nonfrost-susceptible gravel, sand, screening, or similar material. This bottom of the base or subbase will be designed as a filter between the subgrade soil and the overlying material to prevent mixing of the frost-susceptible subgrade with the nonfrost-susceptible base during and immediately after the frost-melting period. The gradation of this filter material shall be determined using these guidelines:

- To prevent the movement of particles from the frost-susceptible subgrade soil into or through the filter blanket, all of these must be satisfied:

$$\frac{\text{15 percent size of filter blanket}}{\text{85 percent size of subgrade soil}} \leq 5$$

$$\frac{\text{50 percent size of filter blanket}}{\text{50 percent size of subgrade soil}} \leq 25$$

- The filter blanket in the above case prevents the frost-susceptible soil from penetrating; however, the filter material itself must also not penetrate the nonfrost-susceptible base course material. Therefore, the filter material must also meet the following requirements:

$$\frac{\text{15 percent size of base course}}{\text{85 percent size of filter blanket}} \leq 5$$

$$\frac{\text{50 percent size of base course}}{\text{50 percent size of filter blanket}} \leq 25$$

- In addition to the above requirements, the filter material will, in no case, have 3 percent or more by weight of grains finer than 0.02 mm.

A major difficulty in the construction of the filter material is the tendency of the grain-size particles to segregate during placing; therefore, a $C_U > 20$ is usually not desirable, For the same reason, filter materials should not be skip- or gap-graded. Segregation of coarse particles results in the formation of voids through which fine particles may wash away from the subgrade soil. Segregation can best be prevented during placement by placing the material in the moist state. Using water while installing the filter blanket also aids in compaction and helps form satisfactory transition zones between the various materials, Experience indicates that nonfrost-susceptible sand is particularly suitable for use as filter course material. Also fine-grained subgraded soil may workup into an improperly graded overlying gravel or crushed stone base course. This will occur under the kneading action of traffic during the frost-melting period if a filter course is not provided between the subgrade and base course.

For rigid pavements, the 85-percent size of filter or regular base course material placed directly beneath pavement should be ≥ 2.00 mm in diameter (Number 10 US standard sieve size) for a minimum thickness of 4 inches. The purpose of this requirement is to prevent loss of support by pumping soil through the joints.

Pavement Design

Pavement may be designed according to either of two basic concepts. The design may be based primarily on—

- Control of surface deformation caused by frost action.
- Provision of adequate bearing capacity during the most critical climatic period.

Control of Surface Deformation. In this method of pavement design, a sufficient combined thickness of pavement and nonfrost-susceptible base is provided to reduce subgrade frost penetration. Consequently, this reduces pavement heave and subgrade weakening to a low, acceptable level.

Provision of Adequate Bearing Capacity. In this method, the amount of heave that will result is neglected and the pavement is designed solely on the anticipated reduced subgrade strength during the frost-melting period.

Detailed design methods used in determining the required thickness of pavement, base, and subbase for given traffic and soil conditions where frost action is a factor are described in *FM 5-430*.