Seepage, Drainage, and Flow Nets

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JOHN WILEY & SONS, INC. New York · London · Sydney

CHAPTER FIVE

Filter Design

5.1 BASIC REQUIREMENTS OF FILTERS AND DRAINS

Many types of engineering works are constructed on or in soils and rocks which are filled with water. The process by which percolating water or groundwater is removed from soils and rocks by natural or artificial means is called *drainage*. Sound rocks usually can be drained simply by allowing water to escape freely at exposed surfaces in drain wells, tunnels, etc., since these materials have sufficient cohesion to resist erosion; but soft, weathered rocks, and most soils present more difficult drainage problems, as unprotected surfaces of these materials can be eroded by the forces of escaping water. If the erosion process is permitted to begin, it can lead to clogging of filters and drains, and in extreme cases, to piping failures. Consequently, drainage surfaces of erodible soils and rocks must be covered with special protective layers that allow the water to escape freely but hold the particles firmly in place.

To some degree porous wicks of cloth or paper, fiber glass blankets, and other manufactured products are used as filter and drain materials, but the predominating drainage material is porous mineral aggregate. Good quality aggregates are virtually indestructible, relatively incompressible, widely available, and relatively inexpensive. When used correctly, porous drainage aggregates can have a vital part in the permanent performance of a great many kinds of civil engineering works. They are frequently used in drainage systems in conjunction with slotted, jointed, or porous pipes, which aid in the collection and removal of seepage.

Filters and drains can provide permanent security against the damaging actions of seepage and groundwater; however, certain fundamental requirements must be strictly enforced. If filters and drains are to serve their intended purpose, the materials used in their construction must have the correct gradation (Sec. 5.2), and they must be handled and placed with care to avoid contamination and segregation (Sec. 5.8). Also, they must be well compacted to reduce the possibilities of localized changes in grading taking place by the dropping of fines through void spaces. Close control is required in the production, handling, and placement of the materials, since even a single improperly constructed portion of a filter can lead to failure.

Many of the problems associated with the design of adequate filters and drains stems from the needs for satisfying two conflicting requirements.

1. Piping requirement. The pore spaces in drains and filters that are in contact with erodible soils and rocks must be *small* enough to prevent particles from being washed in or through them.

2. Permeability requirement. The pore spaces in drains and filters must be *large* enough to impart sufficient permeability to permit seepage to escape freely and thus provide a high degree of control over seepage forces and hydrostatic pressures.

When small quantities of seepage are to be removed, a single layer of well-graded, moderately permeable material meeting both of these requirements may serve the dual roles of filter and drain. But when large quantities of seepage are to be removed, a fine filter layer usually is needed for the prevention of piping, and a coarse layer is needed for the removal of water. Such systems are called *graded filters.* They may contain *more* than two layers. Filters that are covered with surcharges to prevent uplifting by seepage forces are called *loaded* filters or *weighted* filters.

5.2 PREVENTION OF PIPING

General

To prevent piping, water-bearing erodible soils and rocks must never be in direct contact with passageways larger than some of the coarsest soil or rock particles. In nature piping failures often are exhibited by sink holes that form in arid and semiarid lands when fine sand, silt, loess, clay, etc., wash into subterranean tubes or cracks. Parker (1963) points out that piping is an important geomorphic agent in the development of landforms in the drylands.

Many engineering works produce large hydraulic gradients that are conducive to piping. When sewers are constructed below the water table in erodible sand or silt, joints must be meticulously sealed, otherwise serious infiltration is likely to occur. When cracks developed in a deep trunk sewer in Seattle, Washington, a tremendous cavity formed in the soil above it, causing a major repair problem. Piping is a common cause of failure in overflow weirs, earth dams, reservoirs, and other hydraulic structures (Chap. 1). Whenever filters and drains are required for the contrtol of seepage and groundwater in relation to structures, they should have a high degree of resistance to piping.

Grading of Drainage Aggregates to Control Piping

To prevent the movement of erodible soils and rocks into or through filters, the pore spaces between the filter particles should be small enough to hold some of the larger particles of the protected materials in place. Taylor (1948) shows that if three perfect spheres have diameters greater than six and one-half times the diameter of a smaller sphere (Fig. 5.1*a*), the smaller spheres can move through the larger. Soils and aggregates are always composed of *ranges* of particle sizes, and if the pore spaces in filters are small enough to hold the 85% size (D_{85}) of adjacent soils in place, the finer soil particles will also be held in place (Fig. 5.1*b*). Exceptions are gap-graded soil and soil-rock mixtures (Sec. 5.3).

Bertram (1940), with the advice of Terzaghi and Casagrande, made laboratory investigations at the Graduate School of Engineering, Harvard University, to test filter criteria that had been suggested by Terzaghi; he established the validity of the following criteria for filter design:

$$\frac{D_{15}(\text{of filter})}{D_{85}(\text{of soil})} < 4 \text{ to } 5 < \frac{D_{15}(\text{of filter})}{D_{15}(\text{of soil})} \qquad (5.1)$$

The left half of Eq. 5.1 may be stated as follows.

Criterion 1. The 15% size (D_{15}) of a filter material must be not more than four or five times the 85% size (D_{85}) of a protected soil. The ratio of D_{15} of a filter to D_{85} of a soil is called the *piping ratio.*

The right half of Eq. 5.1 may be stated as follows.

Criterion 2. The 15% size (D_{15}) of a filter material should be at least four or five times the 15% size (D_{15}) of a protected soil.

The intent of criterion 2 is to guarantee sufficient permeability to prevent the buildup of large seepage forces and hydrostatic pressures in filters and drains. This criterion is discussed in detail in Sec. 5.4.

The work of Bertram was expanded by further experiments by the U. S. Army Corps of Engineers (1941) and the U. S. Bureau of Reclamation (Karpoff, 1955) and others. Frequently some requirements in addition to criteria 1 and 2 are placed on the grading of

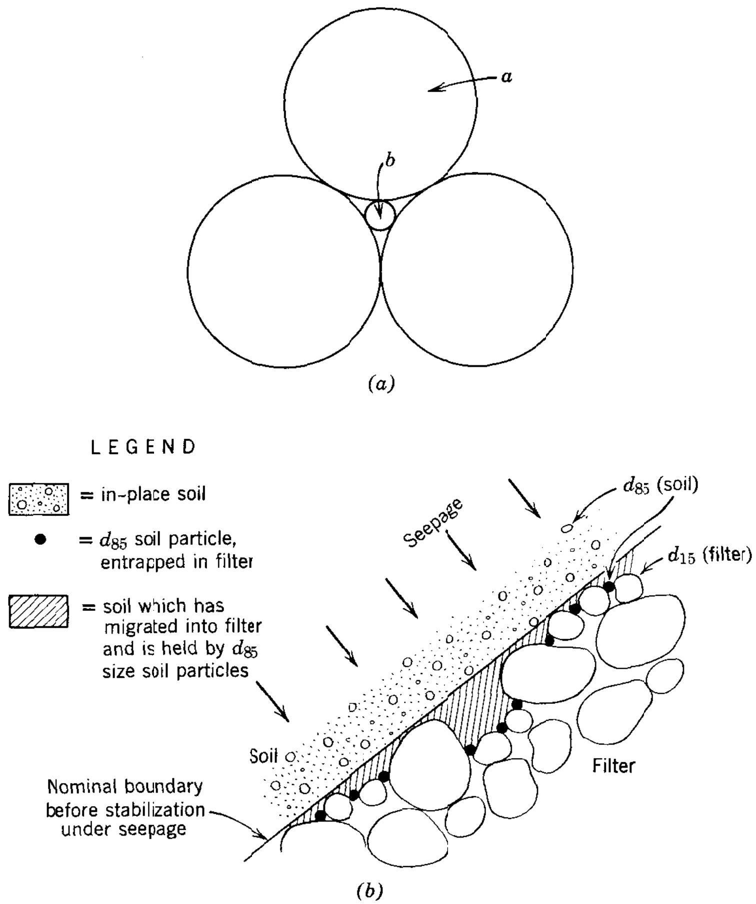

FIG. 5.1 Illustration of prevention of piping by filters. (*a*) Spherical particle *b* will just pass through pore space between three spheres six and one-half times the diameter of *b* (Taylor, 1948). (*b*) Conditions at a boundary between a soil and a protective filter.

filter aggregates. For example, the U. S. Bureau of Reclamation limits the maximum size of filter aggregates to 3 in. to minimize segregation and bridging of large particles during placement. To prevent the movement of soil particles into or through filters, the U. S. Army Corps of Engineers (1955) requires that the following conditions be satisfied:

$$\frac{15\%\text{ size of filter material}}{85\%\text{ size of protected soil}} \leqq 5 \tag{5.2}$$

and

$$\frac{50\%\text{ size of filter material}}{50\%\text{ size of protected soil}} \leqq 25 \tag{5.3}$$

It is seen that Eq. 5.2 is another expression for the relationship given by the left half of Eq. 5.1.

The U. S. Army Corps of Engineers (1955) also states.

> The above criteria will be used when protecting all soils except for medium to highly plastic clays without sand or silt partings, which by the above criteria may require multiple-stage filters. For these clay soils, the D_{15} size of the filter may be as great as 0.4 mm. and the above D_{50} criteria will be disregarded. This relaxation in criteria for protecting medium to highly plastic clays will allow the use of a one-stage filter material; however, the filter must be well graded, and to insure nonsegregation of the filter material, a coefficient of uniformity (ratio of D_{60} to D_{10}) of not greater than 20 will be required.

The U. S. Army Corps of Engineers recommends limiting the piping ratio (D_{15} of filter to D_{85} of soil) to something less than 5 if crushed stone is used for the filter material. The safe ratio is usually checked on important projects by performing laboratory tests with materials to be used in the work. The Corps and the U. S. Bureau of Reclamation also recommend that the grain-size curves of filters and protected layers be somewhat parallel to each other. This is the objective of the relationship expressed by Eq. 5.3.

Sherard, et al. (1963) make the following additional rule for the design of filters. "When the protected soil contains a large percentage of gravels, the filter should be designed on the basis of the gradation curve of the portion of the material which is finer than the 1-inch sieve."

Many other experimenters in addition to Bertram, the U. S. Army Corps of Engineers, and the U. S. Bureau of Reclamation have satisfied themselves that criterion 1 will prevent piping. In 1940 the author conducted a series of experiments in which soils were mixed with water, and slurries were poured over filter materials meeting criterion 1. Under these extremely severe conditions a small amount of clay and colloids washed through but nearly all of the material stayed on top of the filters.

In the construction of a military air base in the Pacific Northwest in 1942, an unexpected storm washed topsoil into partially completed trench drains along the edges of the runways. Fortunately a filter layer meeting criterion 1 had been placed in the trenches. Although muddy water entered the drain pipes, topsoil penetrated the filter layer only a small fraction of an inch.

In 1963 the author supervised experiments in which a two-inch layer of screenings was placed over a layer of silt. With the screenings filled with water the surface was compressed many times with a kneading compactor. These tests, which were intended to simulate the action of concentrated highway traffic on saturated subgrades, indicated that when criterion 1 was satisfied, negligible intrusion occurred at the boundary between the soil and the screenings, but when the piping ratio was much above 4 or 5, substantial intrusion took place under the kneading action.

Experience indicates that if the basic filter criteria described in preceding paragraphs are satisfied in every part of a filter, piping cannot occur under even extremely severe conditions. Bertram's original investigations indicated that the grain sizes of uniform filter materials may be up to ten times those of uniform soils before appreciable amounts of soil will move through filters and that Eq. 5.1 usually is conservative. If a protected soil is a plastic clay, the *piping ratio* often can be much higher than 5 or 10, as indicated by U. S. Army Corps of Engineers practice previously noted. But if cohesionless silts, fine sands, or similar soils are in direct contact with filter materials which have piping ratios much above 5 or 10, erosion is very likely to occur. In 1940 the author witnessed earth dam construction with loess soil being compacted adjacent to a drain composed of 6-inch diameter boulders having a piping ratio relative to the loess of around 2000! During the first filling of the reservoir the drain caused serious internal erosion. Eventually the drain was pumped full of cement grout to save the dam.

When coarse rock, coarse gravel, or other coarse materials are used in drains, erodible soils and rocks should be separated from these materials by two or more intervening filters as required, with each adjacent pair designed to prevent piping. Mechanical analysis plots such as are shown in Figs. 5.2 to 5.6 offer a good visual picture of the grain size distributions of individual soils and filter materials, and are useful in developing filter designs.

Although filter criteria are almost foolproof, experience and judgment will reduce the danger of mistakes being made in their application. Several examples of "normal" designs of filters to prevent piping are given in Section 5.3. Precautions that must be taken in designing filters to protect gap-graded soil-rock mixtures and the dangers of severe segregation in filters are described in the last part of Section 5.3. In these examples, the primary control is assumed to be criterion 1, the ratio of the D_{15} size of the filter to the D_{85} size of the protected soils.

Pipe Joints, Holes and Slots

When pipes are embedded in filters and drains, no unplugged ends should be allowed, and the filter materials in contact with pipes must be coarse enough not to enter joints, holes, or slots. The U. S. Army Corps of Engineers (1955a) uses the following criteria for gradation of filter materials in relation to slots and holes:

For slots

$$\frac{85\% \text{ size of filter material}}{\text{slot width}} > 1.2 \tag{5.4}$$

For circular holes

$$\frac{85\% \text{ size of filter material}}{\text{hole diameter}} > 1.0 \tag{5.5}$$

The U. S. Bureau of Reclamation (1965) uses the following criterion for grain size of filter materials in relation to openings in pipes:

$$\frac{D_{85} \text{ of the filter nearest the pipe}}{\text{maximum opening of pipe drain}} = 2 \text{ or more} \tag{5.6}$$

Equations 5.4, 5.5, and 5.6 represent a reasonable range over which satisfactory performance can be expected. The design of a filter containing a drain pipe is illustrated by an example in Sec. 5.3.

5.3 EXAMPLES OF FILTER DESIGNS TO PREVENT PIPING

Historical

Before the development of rational and experimental filter design criteria, drain design was considered more of an art than a science. Designers depended on judgment, instinct, or precedent. In many instances coarse stone or gravel was placed in direct contact with fine-grained soils, with the result that drains often became clogged or soil piped through causing structural failures. Such was the case with *French drains* and *macadam* rock bases used in highway construction after about 1800 A.D. But some of the early road builders wisely placed fine gravel or screenings between fine soils and coarse stone bases and drains; and some of the early dam builders used several layers of stone grading from finer material in contact with the soil to coarser rock or gravel at the centers of drains. Creager, et al. (1950) describe

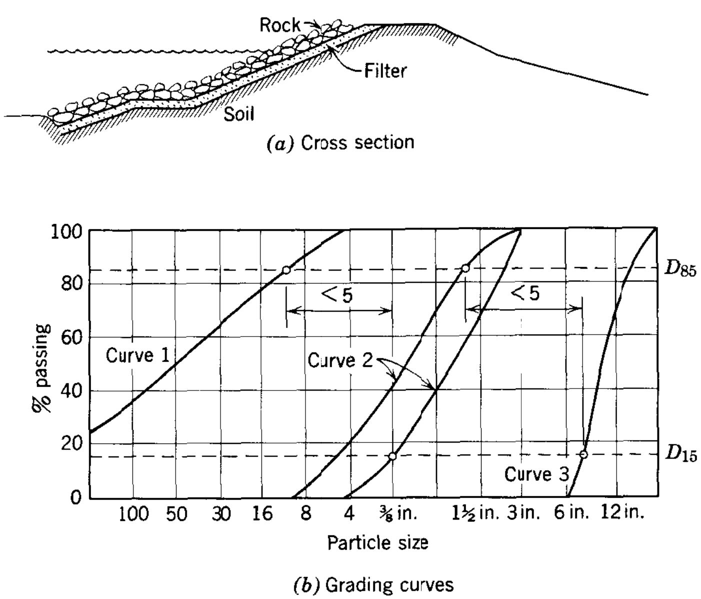

FIG. 5.2 Rock slope protection design to prevent undermining. Intermediate filter or cushion course (curve 2) prevents soil (curve 1) from washing through coarse rock (curve 3). Care must be taken to prevent segregation of intermediate course.

the Tabeaud Dam in California which was constructed in 1902 with a rock drain having two progressively coarser filter zones between the soil and the drain rock.

With the development of rational and experimental filter criteria, the design of filters and drains has become more of a science than an art. Several examples of the application of filter criteria to the design of filters to prevent piping are given in the following paragraphs.

Rock Slope Protection

Frequently coarse rock is placed on the banks of levees, on the upstream faces of earth dams, and in other situations where erodible soils must be protected from fast currents and wave action. If coarse rock is placed directly on fine soil, currents and waves may wash the soil out from under the rock and lead to undermining and failure of expensive protective works, even to failure of the works being protected.

Soil erosion under rock slope protection usually can be prevented by the placement of a filter layer of intermediate-sized material between the soil and the rock. Sometimes erosion can be prevented by the use of well-graded rock containing suitable fines which work to the bottom during placement. A typical rock slope protection with an underlying filter is shown in Fig. 5.2. The slope protection rock (curve no. 3) has a particle size range from 6 in. to 24 in., and a 15% size of about 7 in. The filter layer (curve 2) has a minimum 85% size of about 1.4 in. The piping ratio (criterion 1) = 7 in./1.4 in. = 5. In turn, the soil has an 85% size between sieves 8 and 16. The fine filter has a maximum 15% size of ⅜ in., which is less than five times the 85% size of the soil; hence, according to criterion 1 the soil will not erode through the filter, and the filter is safe from washing out through the rock.

Levee Drain with Perforated or Jointed Pipe

Figure 5.3 shows a typical longitudinal levee drain composed of two grades of filter aggregate surrounding a perforated or jointed

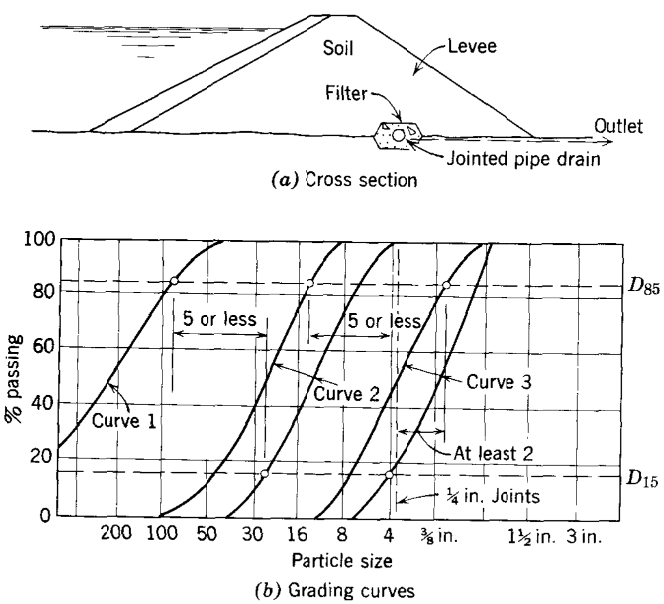

FIG. 5.3 Design of graded filter to protect soil (curve 1) from washing into ¼ in. joints in drain pipe [fine material (curve 2) adjacent to soil; coarse material (curve 3) surrounds pipe].

collector pipe connected with low elevation outlet pipes. Criterion 1 has been applied, as in the preceding example, to establish the 15% size of the coarse drain layer (curve 3) in relation to the 85% size of the fine filter layer (curve 2); and also to establish the 15% size of the fine filter layer in relation to the 85% size of the protected soil. A further check should be made to be sure that the coarse filter material will not enter joints in the pipe. This check is readily made with Eqs. 5.4, 5.5, or 5.6. In this example Eq. 5.6 is used as the criterion. Assuming that joints are not wider than $\frac{1}{4}$ in., a coarse-filter layer with an 85% size (D_{85}) of at least 0.25 in. $\times$ 2 = 0.5 in. is adequate.

Drainage Blanket under Highway in Wet Cut

Often large quantities of groundwater are encountered in highway construction in hilly terrain. When highways must be built in wet cuts, blankets of "permeable" filter aggregate often are placed beneath the structural section to prevent internal flooding, pumping, and deterioration of pavements (Chap. 9). When coarse aggregates are needed for water removal, as they often are, properly graded filter layers must be placed over the soil to prevent clogging of the coarse aggregate. Figure 5.4 shows a satisfactory combination of fine and coarse aggregates that will not become clogged. The coarse upper drainage layer has high permeability to insure rapid removal of groundwater and seepage. To assure permanent functioning of this drainage system without clogging, the fine filter layer on the subgrade (curve 2, Fig. 5.4) has a D_{15} size not more than about five times the D_{85} size of the finest soil on which the road is being built (curve 1), and the coarse filter layer (curve 3) has a D_{15} size not more than about five times the D_{85} size of the fine filter layer. The grading limits for the two filter layers shown in Fig. 5.4 satisfy criterion 1. Methods for designing coarse drainage layers for discharge capacity are described in Sec. 5.4 and illustrated by examples in Secs. 5.5, 5.6, and 5.7.

Some Conditions Detrimental to Filter Performance

The preceding examples represent normal, orthodox filter designs. If soils are not well graded, filters are permitted to become segregated during placement, or other inconsistencies are permitted to occur, the theoretical piping ratio (criterion 1) may appear to be satisfied, yet a filter may be entirely unsatisfactory. Complete dependence on filter criteria without regard for localized conditions that may exist

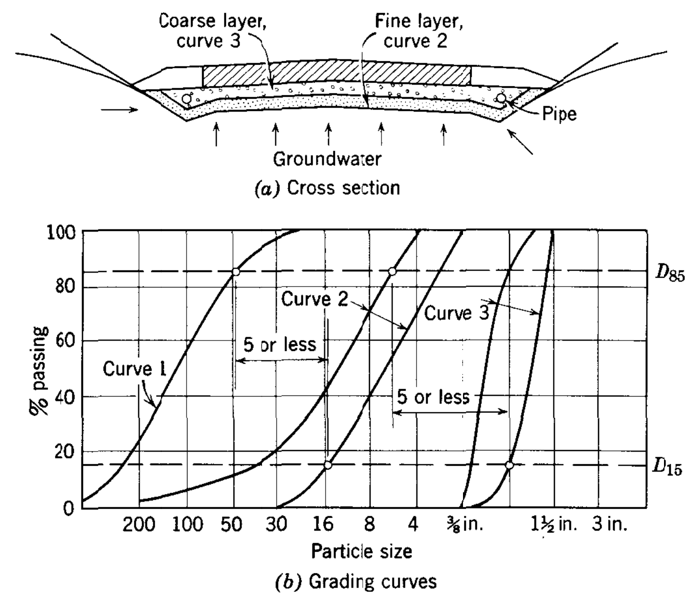

FIG. 5.4 Design of highway roadbed. Fine filter (curve 2) prevents soil (curve 1) from pumping into open-graded drainage aggregate (curve 3). There is considerable groundwater.

in soils or filters can lead to failures. The following examples illustrate this point.

Figure 5.5 shows a filter gradation (curve 3) which according to criterion 1 should protect a soil (curve 1) against piping. If a close look is taken at curve 1 or if some of this material is examined in the field, it will be seen that it is a gap-graded, silty clay soil with scattered particles of "float" rock, not a well graded material as is normally assumed in applying filter criteria. The scattered coarse particles in this soil cannot protect the fine soil particles from migrating through the large pore spaces in the filter. The coarse particles must therefore be ignored and the grading curve for the fine matrix (curve 2) used in selecting grading limits for a protective filter. A much finer graded filter than curve 3 is therefore required for the protection of this soil.

Difficulties can also arise when filters are used for the drainage of soils and bases that are stratified or otherwise variable within a construction area. When filters or drains are placed against variable materials, the *finest* material must be held in place. Mechanical analy-

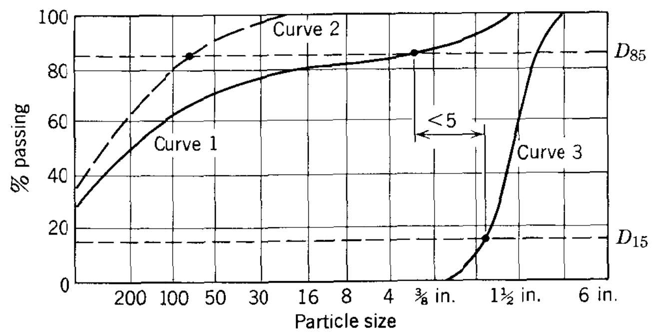

FIG. 5.5 Problems are caused by gap-graded soils. D_{15} size of filter (curve 3) is less than five times D_{85} size of rocky or gravelly soil (curve 1), but fine soil matrix (curve 2) may still migrate through filter.

sis tests can be very misleading when the samples have been obtained by methods that mix the soils within some arbitrary number of feet of a hole or of the sides of a test pit. Methods of sampling should be used that detect detailed variations in gradation and give the gradation of individual strata.

Not only is it possible for protected soils to vary substantially from point to point, as justed noted, but filters can also vary if wide ranges of sizes are permitted, and segregation is allowed during handling or placement. The harmful effect of segregation in filters is illustrated in Fig. 5.6, which shows a fine-grained soil (curve 1) that is to be protected by a filter (curve 2). The proposed filter (curve 2) has an overall grading that meets criterion 1, since its 15% size is not more than five times the 85% size of the soil. But in handling and placing, extensive accumulations of the coarser sizes are assumed to occur, allowing large pockets of coarse segregated material (curve 3) with a D_{15} size fifty times the D_{85} size of the soil. Segregation in filters can lead to serious erosion of protected soils. If filters and drains are to serve their intended purposes, specifications for these facilities (Sec. 5.8) must be carefully written and strictly enforced.

5.4 PERMEABILITY REQUIREMENTS OF FILTERS AND DRAINS

The Basic Problem

The first requirement of filters and drains (Secs. 5.2 and 5.3) is that they must be safe with respect to erosion and clogging. The

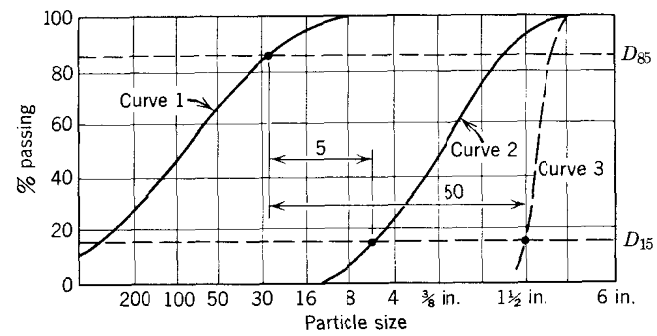

FIG. 5.6 Segregated filter materials also cause problems. D_{15} of unsegregated filter aggregate (curve 2) is five times D_{85} of soil (curve 1), but D_{15} of segregated pockets of coarse filter material (curve 3) is fifty times D_{85} of soil.

second requirement, which can be equally important, is they must have sufficient discharge capacities to remove seepage quickly, without inducing high seepage forces or hydrostatic pressures.

The right half of Eq. 5.1 (Sec. 5.2) was stated as criterion 2: "The 15% size (D_{15}) of a filter material should be at least four or five times the 15% size (D_{15}) of the protected soil." As noted,

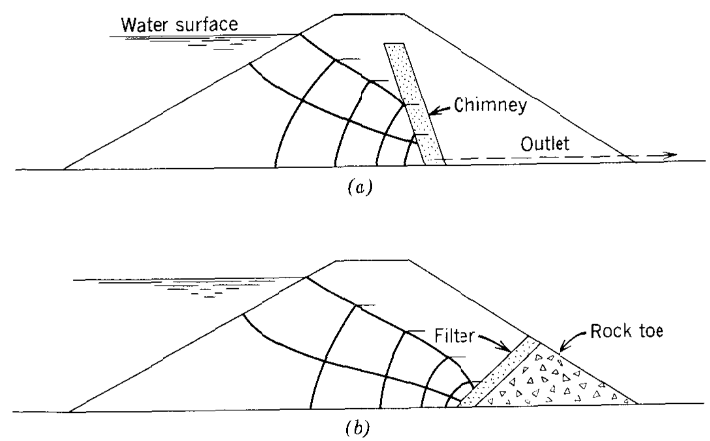

FIG. 5.7 Examples of filters usually working under steep gradients to remove seepage. (a) Dam with chimney drain. (b) Dam with rock toe.