FILTER DESIGN CRITERIA AND
THEIR APPLICATION

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PREFACE

This report is a literature study of mineral aggregate filter criteria and their applications. The areas discussed include history, research, differences in criteria in present use, major applications, design, and construction. The writer has attempted to make use of the major printed sources on the topic and no important source has been overlooked intentionally.

Special emphasis has been placed on the methods employed by the U.S. Army Corps of Engineers. It could be said that this emphasis is not justified. The writer's defense is simply that his entire professional career has been and will probably continue to be with the Corps and the methods, good or bad, employed by the Corps are of more than passing interest. In addition, the Corps has, since the early 1940's taken an active part in the research, development, and use of the mineral aggregate filter in its civil and military design and construction missions.

The author wishes to express his gratitude to the Corps of Engineers, U.S. Army who through its excellent advance study program generously financed this year of study. The author would like to express his appreciation to all those instrumental in his being selected to participation in the program. In particular, the author is especially grateful to Mr. K. Moreman and Mr. J. J. Danaher for their counsel and guidance.

The author's debt to Dr. T. A. Haliburton goes far beyond this report. Without the encouragement, advice, friendship, and the equally important constructive criticism freely given by Dr. Haliburton, the author might never have attempted additional advanced study or once attempting it gained as greatly from it. The author is sincerely and deeply grateful.

The author wishes to express his appreciation to Dr. J. V. Parcher and Dr. R. N. DeVries, committee members, for their counsel and excellent instruction associated with this report and other studies.

The author would like to express his heartfelt gratitude and extend his sincere sympathy to his wife, Gwen, who faithfully carried the burdens of raising our two happy, healthy, children, Patrick Jr. and Kelly, and running our home while her husband was a thousand miles away pursuing the rewards of higher education.

The author would also like to express his warm regard and gratitude to his mother for her strong support, sharp criticism, and never failing confidence in his ability to accomplish any task.

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INTRODUCTION

Statement of Problem

The effective control of the flow or movement of ground water or impounded water through foundations or earth structures has presented a real and troublesome problem to man since he began to build. The uncontrolled seepage of water has resulted in landslides, and has damaged buildings and destroyed dams throughout the history of civilization.

The detrimental effects of seepage can sometimes be successfully controlled by the use of a properly designed and constructed filter or drain. The filter may be used to control the indiscriminate flow of water and to prevent particles from the saturated soil mass being transported by flowing water.

A number of materials such as fiberglass or paper blankets have been used as filters. Currently, thin porous sheets of plastic material are under study and have had some limited use (1). However, the most widely used material is graded mineral aggregate such as crushed rock, gravel, and sand.

The design of aggregate filters is, at first inspection, a rather simple application of criteria (to be described in detail later) based on the diameters of certain key percentages of the in situ soil and the proposed filter material such that the permeability of the filter will insure drainage without permitting the in situ soil to migrate through or clog the filter. However, these criteria may result in widely varying filter designs, while on occasion it is extremely difficult to apply such criteria to certain soils. It also appears that the criteria are in many cases ultraconservative and therefore uneconomical. In short, the results of a design often appear almost arbitrary. The seemingly innocent look of the mathematical expressions of the criteria is deceiving and leads to indiscriminate application.

Many engineers, particularly in earth dam design, agree on the necessity of various type filters to combat certain conditions but will devote a minimum of study to the actual design of the filter itself. Highway engineers seem particularly reluctant to spend money on properly designed and constructed filters or in many cases on any filters at all. In the writer's opinion, part of the problem is that many engineers do not fully understand the basis of filter criteria, their implications, or their limitations.

Improperly worded specifications and poor construction methods are other factors which result in filters that are either inadequate or completely ineffective.

Scope of Report

The scope of the report will in general cover the state of the art of filter design, application, and construction. The basis of the criteria in use today was introduced approximately 50 years ago and a brief discussion of its historical development is presented. The major topic is the general criteria presently used by the rank and file design engineer. A number of modifications to the general criteria for particular conditions, as proposed by various authors or agencies, is presented. A discussion of noteworthy research conducted to evaluate existing criteria and analyses of filters by laboratory methods are included. A number of possible applications of filters such as riprap filter blankets and toe drains are given, followed by general comments on specifications and field construction practices. Conclusions and recommendations by the writer conclude the discussion. The Appendix presents an example of filter design calculations and considerations.

CHAPTER II

A BRIEF OUTLINE OF THE HISTORICAL DEVELOPMENT OF AGGREGATE FILTERS

Early Applications--An Art

The general concept of using a permeable aggregate interface with a fine-grained soil to allow the soil to drain is a very old idea. The so-called French drains and macadam rock base courses used in the construction of highways, applying the idea in actual construction were first used 1800 A.D. (2). These drains were constructed more by art than science and often became ineffective or resulted in piping failures. Many drains consisted of coarse aggregate interfaced with fine-grained soils which allowed the soil to migrate through the filter material, causing clogging of the drain or piping failures in the fine-grained soil. Some drains were constructed with fine aggregate between the coarser aggregate and the soil, thereby producing a filter similar to those in use today.

Art Becomes More Scientific

Cedergren (2) states that Creager, et al. (1950) reported on the use of a rock drain with two progressively coarser filter layers separating the rock from the soil, in the Tabeaud Dam in California in 1902. However, Karl Von Terzaghi is credited with development of the basic filter design criteria in use today. Terzaghi reportedly developed and used the first filters (as we know them today) while working with overflow dams in the Austrian Alps in the 1920's (3). He was granted a patent for his design in 1922 by the Austrian Patent Office (3). Parcher and Means (4) indicate that Terzaghi based his design method on studies he conducted while working with filters for several dams in South Africa.

The criteria proposed by Terzaghi in the 1920's was a milestone for the design of filters and is still the general basis for the majority of design methods used today. However, the criteria have been the subject of many investigations and studies in the past half century and modifications have resulted.

The Growth of the Science

The next major effort following Terzaghi's original work with filter criteria and design appears to be the experimental studies performed by G. E. Bertram (3) at Harvard University in 1938-1939 and reported in 1940. Bertram received advice from both Terzaghi and A. Casagrande while conducting his investigations (2). The U.S. Army Corps of Engineers (5) published a report in November, 1941, on investigations conducted at the Waterway Experiment station on filter material, both from the viewpoint of the protected soil and the infiltration of filter material into underdrain pipes placed in filters to remove collected water from the filters. Terzaghi and Peck (6) indicate experimental work on the "essential requirements of filter material" was done by the U.S. Bureau of Reclamation in 1947. Between 1946 and 1948 the Corps of Engineers (7) conducted a major investigation on filter criteria and the stability of filters for the Enid and Grenada Dams in the Mississippi Valley. In 1953 the Corps of Engineers (8) published a report on studies conducted by laboratory investigations on the usefulness of concrete sand and gravel aggregates as filter materials. The report included a comparison of design criteria used at the Waterways Experiment Station and those employed or proposed by other agencies. K. P. Karpoff (9) (U.S. Bureau of Reclamation) published a paper on the use of laboratory tests to develop filter criteria in 1955.

In addition to these major studies cited, there have been many other investigations, both experimental and empirical, dealing with filters in general or their specific applications. These will be discussed in Chapter III.

CHAPTER III

FILTER CRITERIA AND THEIR DEVELOPMENT

The Filter Mechanism

Before presenting the mathematical expression of Terzaghi's 1920 development of the first scientific approach to filter design a simplified discussion of the mechanics of a filter as Terzaghi defined them seems appropriate. The filter must accomplish two fundamental missions. First, it must not allow soil particles from the soil mass it is serving to pass through or into the filter in any appreciable amount. If soil particles in sufficient amounts are eroded by seepage forces and transported through the filter in the seepage water the integrity of the soil mass is eventually destroyed and failure is imminent. Equally dangerous is the case where soil particles penetrate the filter in sufficient amounts to clog the filter and reduce or defeat its function. The hydrostatic forces in the soil mass will increase and again failure of the soil mass may be imminent. The term used to label the requirement the filter must meet in order to prevent such occurrences is the piping criterion. The piping criterion simply stated is--the voids in the filter must be small enough that the soil particles from the protected soil mass will not penetrate or pass through the filter. Second, the filter must have a permeability high enough, relative to the soil mass, to permit the seepage water to flow through the filter without inducing large seepage or hydrostatic forces in the filter that would endanger the stability of the filter. In other words the filter is subject to piping requirements just as is to the protected soil mass. It must be of sufficient permeability to drain the soil mass and to drain itself while restricting its internal seepage forces to relatively small values. This requirement is called the permeability criterion and simply stated says that the voids in the filter material must be large enough to allow seepage water to escape freely from the filter.

It is interesting to note that the two requirements or criteria represent a paradox. One requires that the filter have small voids to retain the soil while the other requires that the filter have large voids to drain the seepage water. The value of Karl Von Terzaghi's criteria lies in his approach to achieving a satisfactory compromise between the conflicting requirements by controlling the void sizes in the filter with regard to both the particle sizes of the soil and the necessary restraints of having small seepage forces in the filter.

Symbol Convention Used in Grain Size Criteria Expressions

The symbols used to express the grain size criteria will have the general form as follows:

$\text{Diameter}_{(P)}$ = Diameter of the particle size of the material representing P percent smaller than a given size on weight basis from sieving of the material.

A lower case "d" will be used to indicate the diameter of the protected soil mass served by the filter. An upper case "D" will indicate filter particle diameters.

Examples:

d_{15} - the diameter of the 15 percent size of the soil mass.

D_{15} - the diameter of the 15 percent size of the filter material.

Grain Size Criteria for Filter Design

Terzaghi's Criteria

Terzaghi developed an empirical criterion based on the grain sizes of the soil and the filter that fulfills the requirements of a filter as defined in the previous section. The criterion is:

$$\frac{D_{15}\text{ (of filter material)}}{d_{85}\text{ (of the soil)}} < 4 \text{ to } 5 > \frac{D_{15}\text{ (of filter material)}}{d_{15}\text{ (of the soil)}}$$

The left side of the expression states that the diameter of the 15 percent size of the filter material should be less than 4 to 5 times the diameter of the 85 percent size of the soil adjacent to the filter. If this criterion is met Terzaghi postulates that piping of the soil would not occur. The ratio of these two diameters is often called the piping ratio. Actually what occurs is that the d_{85} of the soil is trapped by the D_{15} of the filter, which prevents the remaining soil particles (particles larger than d_{15}) from entering the filter past the d_{85}-D_{15} particle screen. It follows that until the filter skin is made by the d_{85} soil particles some soil smaller than d_{85} will pass through the filter. Figure 1 illustrates the point by showing the soil-filter

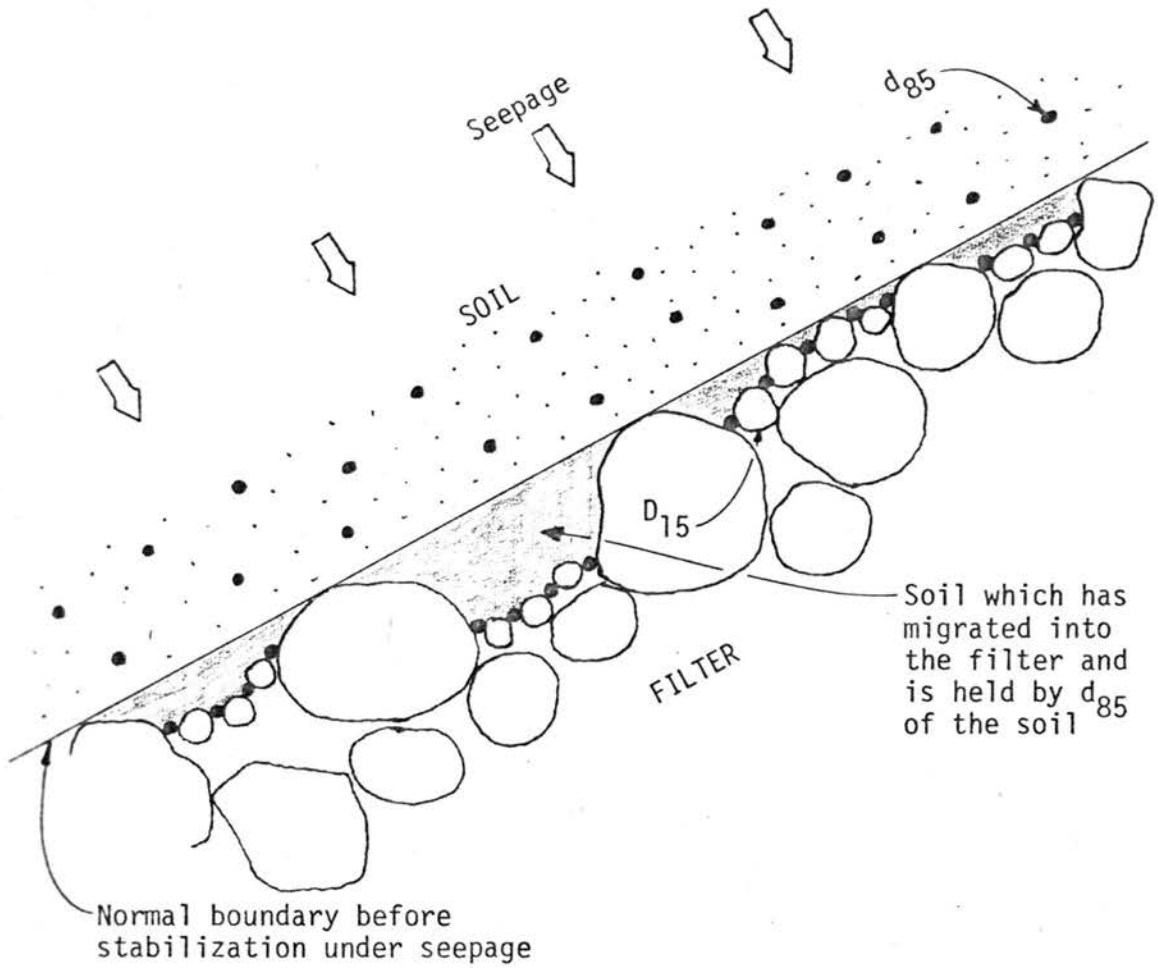


Figure 1. Boundary Conditions Between a Soil and a Filter (After Cedergren, 2)

relationship and the effects of the d_{85} material forming a secondary filter layer or skin, being retained by the D_{15} material in the filter.

The right side of the expression is to assure that the permeability of the filter is such that detrimental seepage forces will not build up in the filter since seepage water can readily drain from the filter. This expression is generally referred to as the permeability criterion but as earlier noted could be considered a piping criterion for the filter where as the left side is a piping criterion for the soil. The basis for considering the permeability criterion as a piping criterion for the filter can be explained by considering what the criterion accomplishes by limiting the magnitude of the seepage force. The magnitude of the seepage force is dependent on the hydraulic gradient present in the filter. Should the hydraulic gradient exceed a critical limit, piping of the filter material may occur if the filter is not retained by a covering material of sufficient weight to counter the detrimental flows. Seepage forces and the hydraulic gradient will be discussed in more detail later in this chapter. The criterion states that the diameter of the 15 percent size of the filter material must be 4 to 5 times as large as the diameter of the 15 percent size of the soil.

It should be noted that the permeability criterion only assures that the permeability of the filter is adequate for free drainage. It does not guarantee that drainage will occur. For drainage to occur the filter must have sufficient cross-sectional area to accommodate the quantity of the seepage. The criterion provides no indication of the physical dimensions of the filter structure. Methods are available for the proper analysis of the area required and will be discussed later in this report.

It is interesting to note that a text published by Terzaghi (10) in 1943 has no real discussion of filter criteria nor does it present his criteria. A later text that Terzaghi and Peck (11) co-authored and published in 1948 did give the Terzaghi criteria but is very limited in its discussion. The second edition (6) published in 1972 again omitted Terzaghi's criteria and instead presents criteria developed by the U.S. Bureau of Reclamation, which only faintly resembles Terzaghi's criteria.

Flow, Gradient, and Voids in Relation to Terzaghi's Criteria

Taylor (12) states that since the velocity of the seepage water is "essentially the same" in both the soil and the filter, Darcy's Law would suggest that the gradient is proportional to the reciprocal of the permeability. Darcy's Law is:

$$q = KiA$$

Where q = quantity of water flowing through a soil per unit of time

K = permeability of the soil

i = hydraulic gradient in the soil

A = cross-sectional area of flow

It should be noted that the expression Ki is the velocity for average flow not the true velocity of flow in the soil, because the water must flow around the soil particles through void channels. Therefore the true velocity is higher than the discharge velocity. The hydraulic gradient i is the difference in head between the point of entry of water and its discharge point divided by the length of flow between the two points, or mathematically:

$$i = \frac{h_1 - h_2}{L}$$

Where h_1 = entry point of water

h_2 = discharge point

L = length

Means and Parcher (13) state that Darcy's Law applies to all soils except very coarse-grained materials, since it is valid only where flow is laminar and the flow path is similar to a capillary tube. The conclusion implied is that flow in coarse-grained material is turbulent and the flow channels are not similar to capillary tubes. Laboratory investigations at Pennsylvania State University suggest that flow is laminar for grain sizes of 0.5 mm or smaller (13).

Taylor (12) also observed that permeability is approximately proportional to $(D_{15})^2$, which would indicate that for filters meeting Terzaghi's permeability criterion the seepage forces per unit of volume in the filter will be on the order of 1/16 to 1/25 those in the soil. This can be verified by a relatively simple exercise using Hazen's formula, Darcy's Law, Terzaghi's permeability ratio, and the seepage force expression. Hazen's formula and the seepage force equations are (13):

Hazen's Formula: $K = CD_e^{\,2}$

Where K = permeability

C = a constant (for coarse sands and gravels approximately equal to 100 CM^{-1} Sec^{-1})

D_e = (generally $D_e = D_{10}$) the effective grain size or the diameter of the grain size of a perfectly uniform material with only one grain size but which has the same permeability as the actual sample for which D_{10} is available. For all practical purposes, the emperical relation $D_e \approx D_{10}$ implies that the finer fraction of a soil mass controls its permeability.

Seepage Force: $F_{sp} = i\gamma_w$

where F_{sp} = the force exerted by a unit volume of water dropping through a head loss per unit of distance traveled.

Hazen found that, generally, the effective grain size can be assumed as the 10 percent size. For our purposes we must take Terzaghi's 15 percent size. The proof (using Hazen's $K = C(D_e)^2$ for Terzaghi's Permeability Criterion) is generally as follows:

$d_{15} = 4D_{15}$(or $5D_{15}$) which is a ratio of 1 to 4 (or 5)

$K_{soil} = C(1)^2$ $\qquad$ $K_{filter} = C(4D_{15})^2$ (or $5D_{15})^2$

From Darcy: $i = q/KA$

Substituting in: $F_{sp} = i\gamma_w = q/KA\gamma_w$

$$q_{soil} \approx q_{filter}$$

$$A_{soil} \approx A$$

$$\gamma_{w_{soil}} = \gamma_{w_{filter}}$$

Reduces: F_{sp} ; $1/K_{soil} \propto 1/K_{filter}$

Substituting in K from Hazen: $1/C(1)^2 \propto 1/C(4)^2$

This results in the F_{sp} in the filter being equal to 1/16 ($d_{15} = 4D_{15}$) to 1/25 ($d_{15} = 5D_{15}$) those in the soil for Terzaghi's range of permeability criterion.

The mechanics of piping are also related to seepage forces. The forces are assumed to act along the flow lines (in the direction of flow). If the flow is vertical to a more or less horizontally exposed soil surface, the only force available to counter the seepage force is the buoyant weight (submerged weight) of the soil particles. If the F_{sp} is equal to or greater than this weight, the downward force of the soil particles from their weight is overcome and the soil mass is unstable. When the seepage force exceeds the downward weight of the soil particles piping (erosion of particles by the seepage water) can occur. The F_{sp}, as previously defined, is a function of the hydraulic gradient i. When the submerged soil weight is equal to the gradient i, the system is in equilibrium. Therefore the gradient i can be used to express the stability of the soil mass subject to seepage forces. In this case the gradient i is called the critical hydraulic gradient and is derived as follows:

$$F_{sp} = i\gamma_w$$

For equilibrium: $i\gamma_w = \gamma_{sub}$

Therefore the critical gradient is: $i_c = \gamma_{sub}/\gamma_w$

Where F_{sp} = seepage force

i = hydraulic gradient

γ_w = unit weight water

γ_{sub} = unit submerged weight soil

i_c = critical gradient

If the direction of flow is upwards and i_c is equal to 1, the soil-water system is in equilibrium but unstable. If i_c exceeds 1 (seepage force per unit volume is greater than the buoyant unit weight of the soil) the pressure between the soil particles is zero and piping can occur. Terzaghi's permeability criterion controls piping in the filter by insuring that the permeability is high enough that seepage forces having a critical gradient will not occur.

Parcher and Means (4) use Terzaghi's permeability criterion in a similar approach. They suggest that for the filter to be effective in reducing seepage forces to acceptable values the permeability of the filter should be 16 or more times the permeability of the soil (the writer assumes that the 16 is a product of Terzaghi's ratio of 1 to 4). Using Hazen's formula to express a ratio of:

$$\frac{K_{filter}}{K_{soil}} = \frac{C(D_{filter})^2}{C(d_{soil})^2} = \frac{16}{1}$$

It follows that to obtain a permeability ratio of 16 to 1, the D_e of the filter must equal to $4D_e$ of the soil. In addition, Parcher and Means (4) point out that the most effective filter is one that has a permeability that would reduce the hydraulic gradient as fast as possible. As already discussed, the flow is assumed to be equal between the soil and the filter. Using equal flows and equal areas in the soil and filter one can apply Darcy's Law:

$$q_{soil} = q_{filter}$$

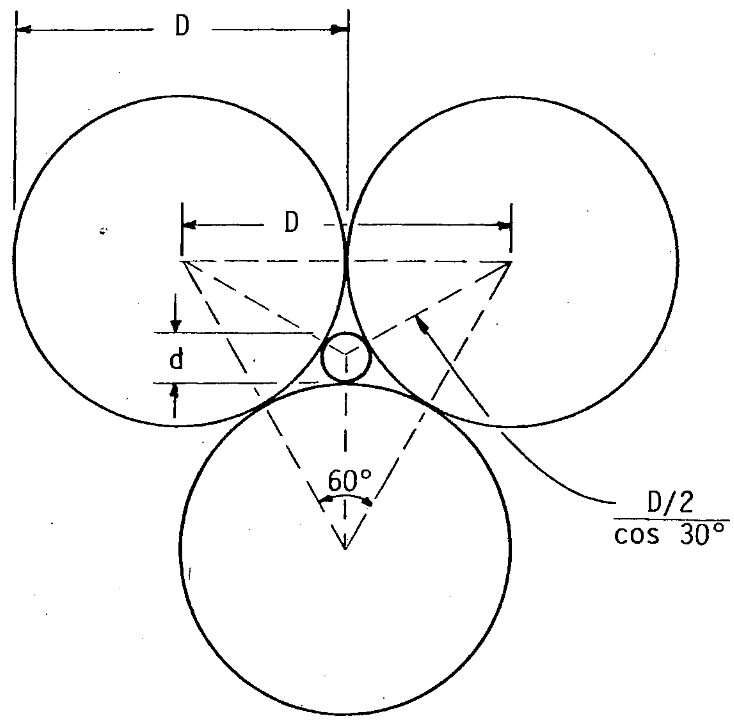
Therefore: $V_s = V_f$

so $K_s i_s = K_f i_f$

From this it can be seen that as K increases i must necessarily decrease. One has little or no control over the permeability and gradient of the soil but by increasing the permeability of the filter a corresponding reduction in the gradient will occur, thereby reducing the seepage force.

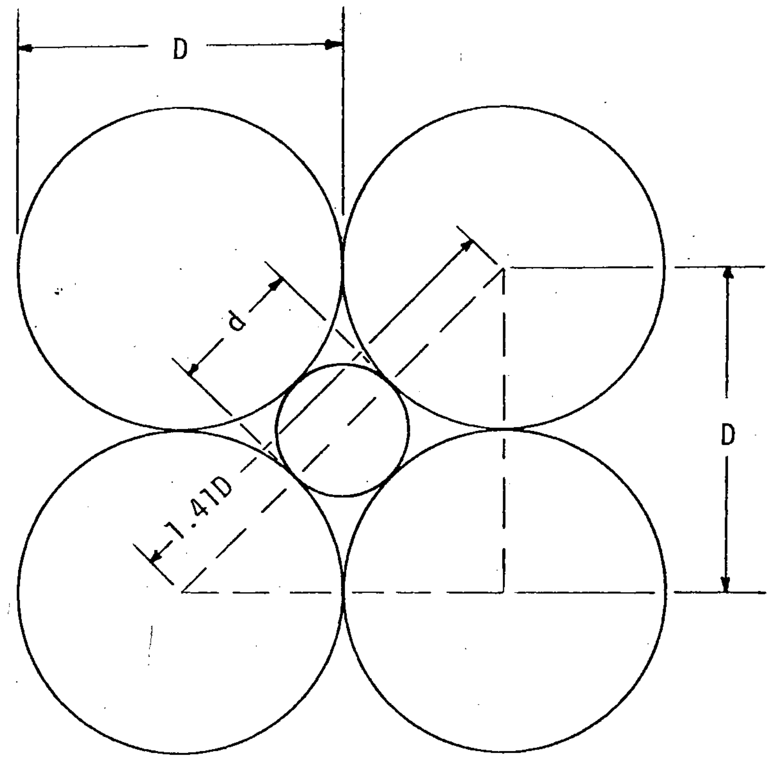
Parcher and Means (4) point out that a material having a single grain size will have the largest void size (high K) and will be the most efficient filter material if the voids are small enough to retain the 85 percent size of the soil.

With regard to void size, Taylor (12) used three equal diameter spheres in the closest packing arrangement possible to demonstrate that for a filter having uniform grain sizes a soil particle would have to have a diameter less than 6.5 times the diameter of the filter material to pass through. This is illustrated in Figure 2. Parcher and Means (4) go through a similar proof for the loosest possible arrangement, which involves four equal diameter spheres, and conclude that for this arrangement the soil would have to have a diameter less than 0.4 times the diameter of the filter material. This is illustrated in Figure 3. This analysis would suggest that for a filter having a uniform grain size the limiting diameter of the filter would be less than 6.5 times the diameter of the soil and perhaps as low as 2.4 times the diameter of the soil if the filter was in a loose-packed arrangement. This suggests that Terzaghi's piping criterion is conservative for close packing and dangerous for loose packing, for filters having uniform grain sizes. However, experimental work by G. E. Bertram (3) on filters of uniform grain size suggest that even Taylor's value of 6.5 is conservative in actual practice. Bertram's work indicates that the filter material may be as much as 10 times the diameter of the soil before appreciable amounts of fine-grained soil pass through the filter. Taylor (12) suggests the limiting size ratio would "appear to depend only in a minor degree on the porosity of the filter material and the sharpness of the grains."



$d = 0.154D$
$D = 6.5d$

Figure 2. Spheres with Dense Packing (After Taylor, 12)



d = 0.413D
D = 2.42 d

Figure 3. Spheres with Loose Packing (After Parcher and Means, 4)

Later Studies and Developments

Bertram--1940

Bertram's work (3) was almost entirely restricted to the study of the criteria for uniformly graded filter material (crushed quartz and Ottawa sand). The testing apparatus used was a special arrangement of a constant head permeability testing device. The test cylinders or sample holders were made of lucite to allow visual observations to be made during testing. The test cylinders were 2 inches in diameter and 6 inches in length. Bertram used hydraulic gradients much larger than would be expected to occur in the field, in order to compensate for the short duration of the tests. The gradients generally ranged from 6 to 20, with durations ranging from several minutes to several weeks. The test specimens were compacted to densities of either 50 percent or 70 percent relative density, depending on the test series. A special series of tests were conducted on specimens 4 inches in diameter and 8 inches in length, to determine if boundary conditions were a consideration. Bertram concluded from the results that the effects of boundary were negligible and the 2 inch by 6 inch cylinders were used for all other testing. The effects of the direction of flow were also examined to see if the results would be affected. It was concluded that the direction of flow had no effect on the test results. An interesting observation was made by Bertram while attempting to mold test specimen in the loosest possible density. Regardless of the care taken in preparing the specimen he always ended with at least 50 percent relative density. Based on these experiments, Bertram projects that regardless of field construction practices filters would always have at least 50 percent relative density. The writer suspects that this is true for uniformly graded sands only.

Only a limited number of tests were performed on grade materials, because of Bertram's "time allotted for . . . investigation."

Bertram's conclusions from the results of his work are as follows:

1. His results were valid for filters having densities of at least 50 percent relative density.
2. Minimum critical ratios for uniform graded filters are:

$$\frac{D_{15}}{d_{85}} \approx 6 \qquad \frac{D_{15}}{d_{15}} \approx 9$$

3. The critical ratios are:
   (a) practically independent of grain shape
   (b) "fairly" constant for the hydraulic gradients investigated, which ranged from 6 to 20.

In addition, Bertram made tentative observations on critical ratios, based on limited testing, for graded materials as follows:

$$\frac{D_{15}}{d_{85}} \approx 6 \qquad \frac{D_{15}}{d_{15}} \approx 26$$

Bertram's conclusions for uniform grain size filter ratios appear conservative based on his results. The ratios of D_{15}/d_{85} ranged from 8.5 to 15.0 with the average in excess of 10. For the D_{15}/d_{15} the results ranged from 6.5 to 11.5 with the average well over 9. In the writer's opinion, Bertram's data is confined to soil (protected soil mass) in the fine sand range. Bertram used no soil having a grain size smaller than a 200 sieve. He restricted the filter material to an upper medium sand size. In some of the initial tests he even washed the "dust" from his samples.

U.S. Corps of Engineers Investigation--1941

In late 1941 the Corps' Waterways Experiment Station (5) published a report covering an investigation of the minimum grain size criterion for filter materials, which would prevent the infiltration of fine-grained soil particles into the filter and would prevent the infiltration of the filter material into "various types of commercial under-drain pipe." The investigation included the use of pyralin permeameters and a 2 feet wide, 4 feet deep, 36 feet long flume. A permeameter using a 3 inch diameter sample was used in the testing of the penetration of fines into a filter material. Generally the relative thickness of the soil was small compared to the filter thickness. It was found early in the testing that visual observations proved the most reliable way to record movement of fines into the filter. Permeabilities were not generally measured as in Bertram's studies.

A permeameter with an 8 3/8 inch diameter was used in testing the infiltration of filter material into under-drain pipes. Porous concrete or perforated wood discs were used to simulate the walls of various types of pipes. The flume was used to test full size sections of under-drain pipe placed within a filter.

After repeated trials a fine sand ranging in size from 0.30 to 0.05 mm was chosen as the material to represent the "soil" for the small permeameter tests. This material was sufficiently small to be transported by very low flows. Small hydraulic gradients were used throughout the investigation. The material used to represent the filter was a mixture of coarse sand and medium to small gravel. As testing progressed the gradation of the filter material was changed by successively removing fines from the material.

The results of the small permeameter tests confirmed Terzaghi's piping criterion as valid. However, several additional requirements were suggested. These are covered in the discussion of the conclusions of the study.

A special test (small permeameter) was conducted with a loosely packed filter sample (6.35 inches high). No "soil" layer was included. After flow was initiated the sample container was repeatedly tapped with a rubber mallet. Several observations were made. The sample height reduced to 6.20 inches. The head loss became nonuniform and the permeability of the top part of the sample increased. The vibrations induced by tapping had caused a migration of filter fines to the bottom of the sample and compaction of the sample. It was concluded that all filters should be packed densely to avoid such an occurrence. In the field an excellent example of a force that would generate vibrations similar to those of tapping is an earthquake.

One very interesting observation made during the small permeameter testing was that when there was no apparent movement (based on visual observations) of the soil into the filter, manometers attached to the test cylinder, indicated that some readjustment had occurred but that it was limited to the top 1/2 to 3/4 inches of the filter. If one relates this to Figure 1 it would seem that the filter skin formed by the penetration of the d_{85} size of the soil is possibly limited to less than 1 inch.

Results from the tests using porous concrete discs in the large diameter permeameter indicated that porous concrete pipes with sealed joints could be used successfully as collectors in filters composed of fine to medium sands, without having to add coarser material. Results of tests with perforated wooden discs indicated that while a uniform filter material was more pervious than a well-graded material of the same average size, the uniform material would "wash out" more readily than the well-graded material. The results also pointed out that filters designs by $D_{15}/d_{85} \leq 5$ were extremely susceptible to infiltration into underdrain pipes having perforations of 3/8 to 5/8 inches. Tests also suggested that pipes having perforations only on the bottom half of their periphery had smaller amounts of infiltration than those having perforations on the top half. Based on all results of the large diameter permeameter tests it was concluded that drain pipes having large diameter openings required multi-layer filters.

The filter material selected for use with the full size flume tests was a mixture of minus 30-mesh concrete sand (70%) and medium gravel (30%). Densities for this material ranged from 118 lbs/cu ft (vibrated and tamped) to 104 lbs/cu ft for the loosest condition. The "soil" used on top of the filter material was a fine to very fine sand. The full size tests generally supported the conclusions drawn from the large size permeameter tests. All tests with pipe where the joints (concrete and clay pipes) were unsealed had excessive infiltration. It was noted that, as expected, the inflows concentrated at these joints. Of the types of pipe tested the tar-coated corrugated (1/4 to 3/8 inch perforations down) and porous concrete pipes with sealed joints were the most satisfactory.

The conclusions presented in this report are of particular value, in a general sense, to designers of collector pipes in filters. Because of their value they are quoted in their entirety as follows:

Filter materials

From the laboratory study of the filter materials and also from the observation of their performance in the flume tests, the following conclusions are summarized:

a. A fine material will not wash through a filter material if the 15 per cent size of the filter material is less than five times as large as the 85 per cent size of the fine base material.

b. In addition to meeting the above size specification, the grain size curves for filter and base materials should be approximately parallel in order to minimize washing of the fine base material into the filter material. [or, at least that at equal ordinates to the two curves (filter and base materials) the particle size of the filter should not be more than a fixed number of times (say twenty-five) larger than the particle size of the base material.]*

c. Filter materials should be packed densely in order to reduce the possibility of any change in the gradation due to movement of the fines.

d. A filter material is no more likely to fail when flow is in an upward direction than otherwise, unless the seepage pressure becomes sufficient to cause flotation or a "quick" condition of the filter.

e. A well-graded filter material is less susceptible to running through the drain pipe openings than a uniform material of the same average size. However, even a filter material having a wide range of gradation cannot be used successfully over a drain pipe having large openings, since enough fine particles to cause serious clogging will move out of the well-graded material into the pipe.

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*Moved from body of text by writer.

Underdrains

The tests on the rate of surface infiltration through the filter into the pipes indicated the following:

a. The rate of infiltration through the filter bed was not materially limited or affected by any of the pipes tested as long as they did not become clogged.

b. Large openings in the drain pipe result in somewhat higher rate of infiltration but also increase the tendency for filter material to collect in and clog the pipe.

c. Drain pipes with perforations around only half or less of their circumference drain the filter more rapidly when the perforations are up, but less material will wash in when the perforations are down.

The tendencies for the filter material to wash into and clog the pipe are of primary importance in comparing the various commercial pipes. Tests performed to determine the amount of materials washed into underdrain pipes showed the following:

a. Perforated drain pipes having many small openings, preferably on the underside of the pipe only, and porous concrete pipes, are less subject to infiltration of small gravel and sand than other types of drain pipe. The smallest quantities of filter material were washed into the porous concrete, the perforated metal and the perforated concrete pipes. The quantity of material washed into the perforated clay with perforations all around the circumference was excessive.

b. The perforated metal and perforated concrete pipe should be placed with perforations down.

c. In the tests of the plain concrete and the clay skip pipes, in both of which drainage was concentrated at the joints, serious quantities of the filter material washed into the pipe.

d. The porous concrete with bevel or lap joint, and the perforated concrete and clay with bell and spigot joint, should be placed with the joints tight and preferably sealed with mortar.

e. The porous concrete pipe will also drain without clogging in clean, medium-fine sands without other filter media, providing the joints are tight.

Where it is feasible to design and use a graded filter, consisting of several layers with coarse gravel near the openings of the pipe, pipes with the larger openings would probably operate satisfactorily.

Filter Investigations for Specific Projects by Corps--1948

In January 1948 the Waterways Experiment Station (7) released a report of an investigation of drainage filters and filter blankets beneath riprap for the Enid and Grenada Dams. The materials used in the investigation were native to the respective project sites and were the materials to be used in actual construction. A series of laboratory tests were conducted to choose the designs which would give optimum performance.

The results of the laboratory investigation for these particlar projects are of general interest only but are an excellent example of confirming (or changing) "paper" designs with laboratory tests.

Of specific interest is that one intent of the investigation was to again check the validity of the $D_{15}/d_{85} < 5$ criterion. In addition, several conclusions resulting from the special tests for the dams are applicable to general design.

The filters used in the testing program were designed by the following:

Piping Criterion (called stability ratio in the report) $\frac{D_{15}}{d_{85}} < 4$

Permeability Criterion (called permeability ratio in the report) $\frac{D_{15}}{d_{15}} > 4$

For perforated collector pipe the following was used:

Circular holes $\frac{D_{85}}{\text{Hole Diameter}} > 1.0$

Slots $\frac{D_{85}}{\text{Slot Width}} > 1.2$

It was further stipulated that while a filter might satisfy the piping and permeability criteria, if the filter was composed of a material that had an excess or lack of certain sizes (therefore not uniformly graded) it might still fail. To avoid this behavior, additional requirements were placed on the filter as follows:

a. The filter grain size curve should be generally parallel to the grain size curve of the protected soil. This can be accomplished by:

$$\frac{D_{15}}{d_{15}} < 20$$

$$\frac{D_{50}}{d_{50}} < 25$$

b. The filter material should be well-graded over the entire grain size curve. It should have no large excess or deficiency of intermediate sizes. A deficiency of intermediate sizes will increase the tendency to segregate during placement of material.

The results of the tests using the above criteria led to several interesting observations on filter performance. All of the soil/filter combinations were stable for steady flows (up or down) when D_{15}/d_{85}

was less than 4.5, regardless of the gradation of the soil or filter. The hydraulic gradients used ranged from 1 to 25. In addition, all tests except one were stable for D_{15}/d_{85} less than 5. However, ratios higher than 5 failed under steady flows. Some of the designs, while ordinarily stable, would fail when subjected to vibrations (tapping) and/or surging. The shape of both filter material and soil grain-size curves have considerable effect on their combined stability.

The results of the tests led to the conclusion that when both the soil and the filter material are more or less uniformly graded (no excess or lack of given grain sizes), the ratio of $D_{15}/d_{85} < 5$ is adequate for design. Based on the testing for this report and the results of previous investigations, additional criteria were recommended in the report as follows:

$$\frac{D_{15}}{d_{15}} > 4 < 20 \qquad \frac{D_{50}}{d_{50}} < 25$$

In cases where either the filter material or the soil are poorly graded it was suggested that the design should be substantiated by laboratory testing.

Corps of Engineers--1953

In 1953 the Waterways Experiment Station published a report of a laboratory investigation on the use of standard concrete sand and gravel (as defined by Corps of Engineers Standards) as filter materials (8). In addition, the report included a comprehensive study and comparison of filter criteria used by the Corps and that used or proposed by other agencies or individuals.

The laboratory investigation was conducted using special permeameters which had lucite sample cylinders. The diameters of the cylinders used were 2 5/8, 5, and 12 inches. The diameter of the cylinder used in any given test was dependent on the particle size of the given sample. An arbitrary rule adopted was that the largest particle of a sample should be less than 1/10 the diameter of the cylinder used for the test. Flow was possible in either an upward or downward direction. A constant head tank was used to regulate flow. The procedures used in placing the sample, saturation, and permeability testing were generally as established by Bertram (3).

All testing analyses investigated the suitability of the following ratios and terms:

Stability Ratio: (piping ratio)	$\frac{D_{15}}{d_{85}}$
Permeability Ratio:	$\frac{D_{15}}{d_{15}}$
Auxiliary Stability Ratios:	$\frac{D_{50}}{d_{50}}$ and $\frac{D_{15}}{d_{15}}$
Hazen's Uniformity Coefficient (C_u)	$\frac{D_{60}}{D_{10}}$ or $\frac{d_{60}}{d_{10}}$

The filter material used in the testing was, in most cases, an artificially blended mixtures of standard concrete sand and gravel as described in "Revised Specifications for Concrete Construction for Civil Works," U.S. Army Corps of Engineers, March 1946.

The first series of tests were conducted with filters composed of the coarsest permissible concrete sand. No vibration was applied and the hydraulic gradients used were 16, 18, and 26. The filters all had C_u values of 5.6 while that of the soil varied from 1.2 to 2.0. All flow was downward. The test results indicated that standard concrete sand was a suitable filter material for fine-grained soils.

The second series of tests were conducted on standard concrete gravel (U.S. No. 4 sieve to 3/4 inch), and investigated its suitability as a filter for standard concrete sand and other selected soils. The hydraulic gradients in the soil portion of the sample varied from 2 to 23. C_u values for the soil varied from 1.2 to a maximum of 6.1 while a value of 2 was maintained for the filter material. Most tests were conducted with both upward and downward flows. All tests were performed for steady flow conditions and vibration. The results of these tests were reported as indicating "to an approximate degree the limiting types" of soil which filters constructed of U.S. No. 4 sieve to 3/4 inch gravel will protect. For steady flow the "stable" ratios for the finest soil tested were:

$$\frac{D_{15}}{d_{85}} \leq 6.0 \qquad\qquad \frac{D_{15}}{d_{15}} \leq 8.5$$

These were limiting ratios when vibratory forces were applied. The filter material was also suitable for the protection of standard concrete sand, although at the extreme limits of the sand (as the soil) and the gravel (as the filter), they were close to the limits of stable performance.

Several observations made during testing are considered worthy of a direct quote:

a. The magnitude of the gradient above a value roughly equal to 1 seems to have little significant effect on the stability of the filter. At higher gradients, however, susceptibility to piping increases when the filter is vibrated.

b. The rate of applying the gradient affects the performance of a filter. The action resulting from applying the gradient rapidly is similar to applying vibration in that the arching or bridging action of the base material is temporarily destroyed.

c. The downward flow condition is believed to be more critical than the upward flow condition only when extraneous forces such as vibration or surging are present. The hypothesis upon which this is based is illustrated on fig. 10 which is a sketch of the upward flow condition. The presence of the arch accounts for the boiling action at the contact surface of the base since it creates a zone of "free material" where no intergranular stresses exist. This effect apparently does not influence the stability of the filter combinations. In downward flow, the arch is also present but the "free material" falls into or through the filter material. When vibration is applied and causes breakdown of the arch in the upward flow condition, it is probable that the "free material" present hinders the flow of material to some extent until a new arch forms.

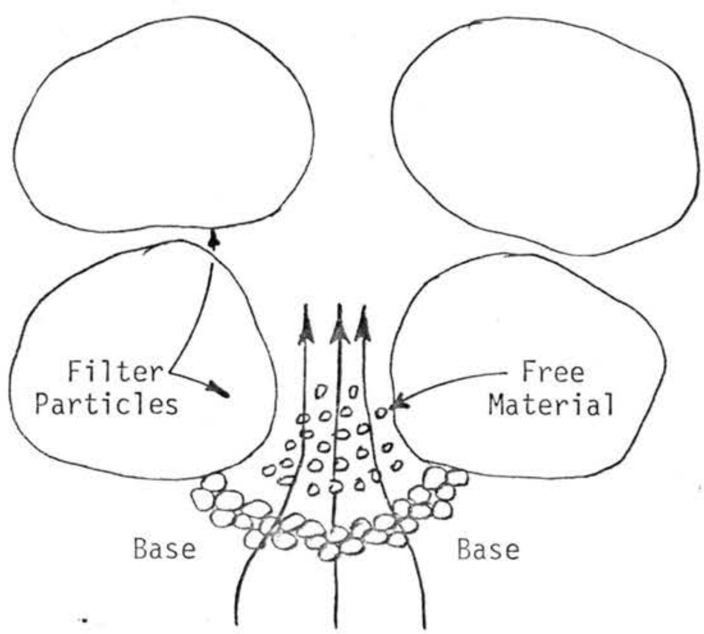


Fig. 10. Arching phenomenon at contact surface of filter and base, upward flow

The third and final series of tests was conducted on mixtures of sand and gravel. These tests were conducted without a soil layer and were intended to check the resistance of the filter material to internal segregation and piping. Only a few combinations of sand and gravel were tested and of those tested the mixture containing 70 percent sand and 30 percent gravel performed best.

The review of existing filter criteria performed by the Waterways Experiment Station included a number of studies already discussed in this Chapter. A summary of the studies and their proposed criteria is shown in Table I, as taken from the Corps' report (8).

The report points out that for a uniform grain-size soil (particles approximately the same size) little difficulty is experienced in filter design. With soils having wide variations in particle size the gradation of the soil becomes a consideration. Most filter criteria are based on the idea that if the 85 percent size of the soil is retained by the filter the soil will be in a stable condition or will not pipe into the filter. Test data support the fact that for widely graded soils the particle size of the soil which will hold the soil mass in place is a function of the gradation of the soil.

In addition, the pore size of the filter affects the design of the filter. The permeability of uniform material varies as the square of the 10 to 20 percent size of the material, and as the square of the pore size. This suggests that the 10 to 20 percent size is directly related to the pore size. Terzaghi's criteria relate the permeability and pore size to the 15 percent size of the material. However, the 15 percent size of a filter is only an approximate measure of the pore size of

TABLE I

SUMMARY OF FILTER DESIGN CRITERIA
(After Corps of Engineers, 8)

Investigators	Base Material	Filter Material	Criteria Developed
Terzaghi 1922	Uncertain whether criteria based on experiments or conservative reasoning		$\frac{D_{15}F}{D_{85}B} < 4 < \frac{D_{15}F}{D_{15}B}$
Bertram 1939	Uniform quartz and Ottawa sands	Uniform quartz and Ottawa sands	$\frac{D_{15}F}{D_{85}B} < 6$, $\frac{D_{15}F}{D_{15}B} < 9$
Newton and Hurley 1940	Well-graded gravelly sand	Natural bank gravels. Finer sizes successively screened out. Fairly uniform filters	$\frac{D_{15}F}{D_{15}B} < 32$, $\frac{D_{15}F}{D_{50}B} < 15$
Waterways Experiment Station 1941 1948	Random material types. Fine to coarse sands	Random types including natural pit-run gravels	$\frac{D_{15}F}{D_{15}B} > 4, < 20$ $\frac{D_{15}F}{D_{50}B} < 25$, $\frac{D_{15}F}{D_{85}B} < 5$ Gradation of filters should be more or less parallel to base. Filter should be well graded
Office, Chief of Engineers	All types	Concrete sand and coarse aggregate generally recommended	$\frac{D_{15}F}{D_{85}B} > 5.0$ $\frac{D_{15}F}{D_{15}B} > 5$
U. S. Bureau of Reclamation 1947	Artificially blended materials of various ranges including uniform material	Artificially blended uniform filters	$\frac{D_{50}F}{D_{50}B} > 5, < 10$
		Artificially blended well-graded filters	$\frac{D_{50}F}{D_{50}B} > 12, < 58$ $\frac{D_{15}F}{D_{15}B} > 12, < 40$
Providence District, CE 1942	All types	Certain general types recommended	Filter design curve C_u of base vs $\frac{D_{15}F}{D_{15}B}$

uniform materials and is, in many instances, unsatisfactory for widely graded materials.

The report attempted to correlate the results of over a hundred filter tests from previous studies of the Corps and others, in an effort to derive empirical criteria for the design of filters. The test results used in the correlation were from the studies tabulated in Table I. Plots of curves for D_{15}/d_{85} versus the uniformity coefficient (C_u) of both the protected soil and filter material were made. From these plots it was concluded that the maximum allowable ratio for D_{15}/d_{85} appeared to decrease as the uniformity coefficient of the soil increased and when the uniformity coefficient exceeded 3, the ratio might not be sufficient by itself to insure filter stability (no piping). The curves also supported observations made by other studies [e.g. Bertram (3)] that for very uniform soils (C_u < 1.5) the D_{15}/d_{85} ratio of less than 5 could be overly conservative. The D_{15}/d_{85} versus C_u of the filter indicated that the increase of the value of C_u had little effect on filter performance but that there was a tendency for the majority of unstable filter-soil combinations to involve a very uniform filter.

Curves for D_{15}/d_{15} versus D_{15}/d_{85} suggested that limiting ratios of 20 and 5, respectively, may be conservative in some instances. The D_{15}/d_{15} ratio could be as high as 40 but the use of this high value would be unsafe unless confirmed by laboratory testing for the particular filter design.

Several other curves were developed but of most interest is a plot of D_{15}/d_{15} versus C_u of the soil. The plot is illustrated in Figure 4 (14). Two curves are developed on the plot. Curve I separates the stable and unstable soil-filter combinations for steady flow. Curve II separates stable and unstable conditions for designs subjected to vibration. Curve I implies that the limiting value of the ratio of D_{15}/d_{15} approaches 40. This limiting value was supported by the testing for this report (8), and by work performed by the Bureau of Reclamation. The use of Curve I for design purposes is limited. It can not be used for gap-graded soils, without modification, since the value of C_u for such materials may have little effect unless normally graded at least below the 60 percent size. The report suggests that "in general, if the material is gap-graded below this size, it is believed a reasonable, and conservative, filter can be designed by assigning a uniformity coefficient based only on the slope of the lower portion of the grain-size curve." It is also suggested that designs be checked by laboratory testing. It was also suggested that Curve I is too conservative for relatively fine-grained soils having too low a permeability to allow any quantity of flow or movement of soil particles. The use of Curve I is limited to stability (piping) characteristics of the filter and to filters which do not have a deficiency or excess of certain sizes.

The differences between Curves I and II were presumed to be due to arching. The curve differences suggest that the maximum allowable ratio of D_{15}/d_{15} under steady flow is approximately twice that for flow under vibratory and surging effects. The arching phenomenon is apparently destroyed or reduced when vibration is introduced, but usually redeveloped when vibration is stopped. The arching effect is also subject to how the gradient is applied. When the gradient was raised instantaneously, arching was appreciably affected. Several

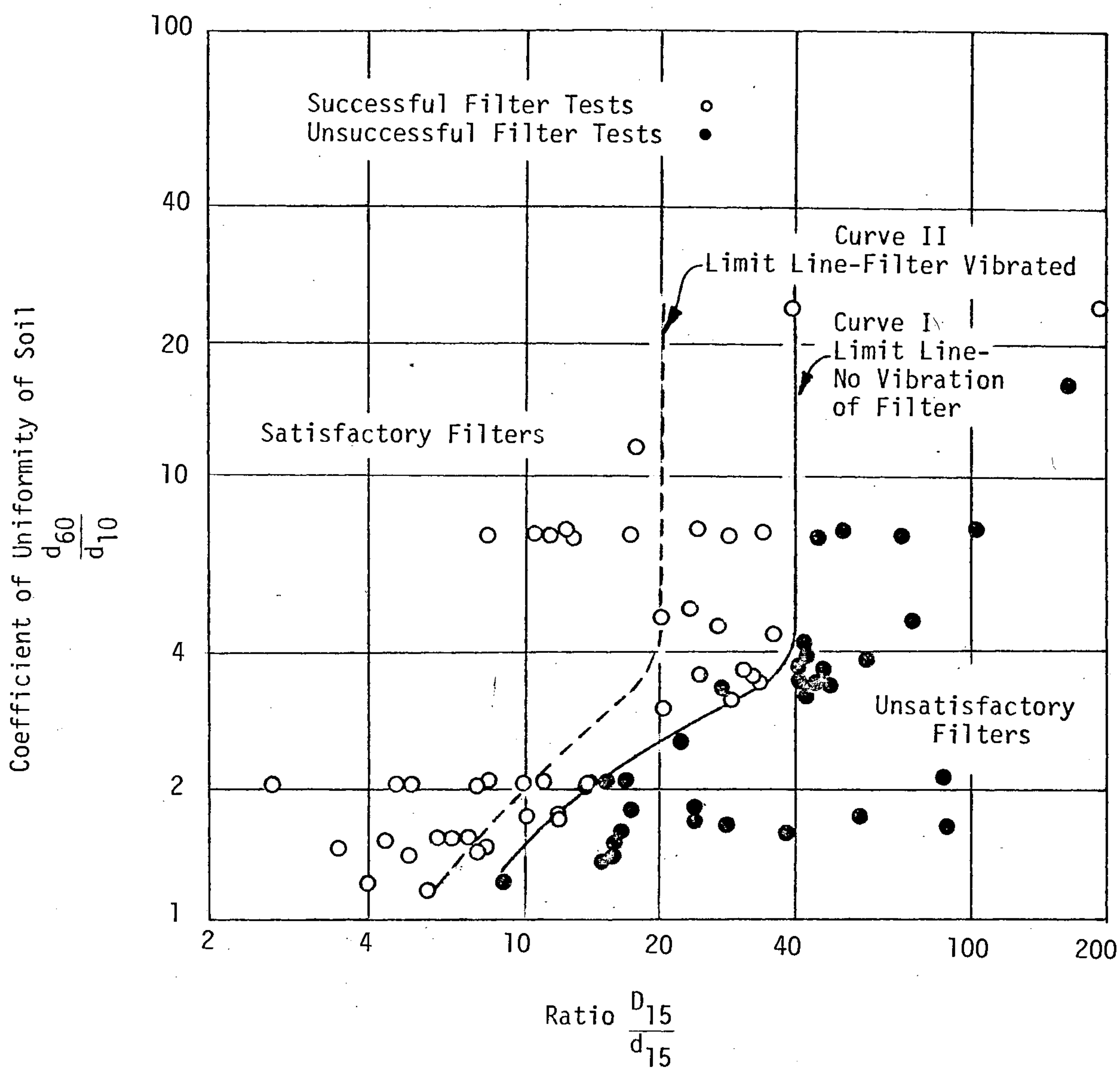


Figure 4. Uniformity Coefficient versus Permeability Criterion (Fig. 17 in Reference 8) (After Thankikachalam, Sakthvadivel, and Kulandaiswamy, 14)

special tests using metal plates with circular holes conducted to observe arching suggested that the arching effect increased with decreasing void ratios, which suggests that a certain critical void ratio exists for a given hole size. Above this void ratio the material is too loose for an arch to form. In one test a hole in the metal plate approximately four times as large as the sand particles effectively held back the sand. Gradients as large as 400 (assuming laminar flow at holes) failed to destroy the arch but a slight vibration was sufficient to temporarily destroy the arch.

The report comments on Terzaghi's permeability criterion of 4 as being "suited for establishing the lower limit of the permeability ratio when the gradients are relatively low." It was reported that the maximum permeability occurred between uniformity coefficients of 2 and 3.

Concerning segregation the report states:

> Uniform filter materials possess the qualities of good permeability characteristics and very little tendency towards segregation. Widely graded filter materials have the advantage of producing a dense, compact mixture with little tendency to erode or pipe. They will tend to segregate, however, depending on the range and shape of the grain-size curve and methods of handling and placement. Gap-graded and concave-shaped curves will tend to segregate more than convex-shaped curves for the same range of particle sizes. It appears that well-graded (straight-line distribution) materials, having a range of approximately one cycle of grain size on a semilogarithmic plot, will probably produce the most balanced filter material.

In summary, the report drew conclusions as follows:

> The following conclusions were derived from the results of the tests performed in this investigation and from correlation of these results with those of similar studies.

a. Standard concrete sand filter.

(1) Standard concrete sand (CE) is a suitable filter material for all materials coarser than the loess tested, and is also considered suitable for fine-grained soils because of the low seepage velocities in such soils.

b. Standard concrete gravel filter.

(1) Standard concrete gravel (CE), No. 4 to 3/4 in., filter can protect effectively a standard concrete sand (CE) base material.

(2) Based on the tests with concrete gravel filters with a widely graded base material $C_u > 4$, filter-base combinations having a $\frac{D_{15}F}{D_{15}B}$ ratio as high as 40 appear satisfactory.

c. Mixture of concrete sand and gravel filters.

(1) The most suitable filter material composed of a mixture of standard concrete sand and gravel aggregates is one having approximately 70 per cent sand and 30 per cent gravel. This is based only on considerations regarding internal stability and permeability characteristics.

d. Review of filter criteria.

(1) Correlation of all assembled filter data indicates that the present Waterways Experiment Station filter criteria for stability $\frac{D_{15}F}{D_{85}B} \leq 5$, $\frac{D_{50}F}{D_{50}B} \leq 25$, $\frac{D_{15}F}{D_{15}B} \leq 20$, are generally satisfactory but are somewhat too conservative in the case of very uniform base materials and base materials that are widely graded. The above criteria are considered suitable where vibration or surging may be expected. For steady flow conditions the following extensions appear warranted:

(a) For very uniform base materials ($C_u < 1.5$) the $\frac{D_{15}F}{D_{85}B}$ ratio may be increased to 6.

(b) For widely graded base materials ($C_u > 4$) the $\frac{D_{15}F}{D_{15}B}$ ratio may be extended to 40.

(2) A more general filter criterion is suggested consisting of a modification of the filter design curve developed by the former Providence District, CE. The filter design curve (see curve I, fig. 17) is based on results of tests on very uniform and widely graded base materials.

(3) Where a filter combination may be subjected to vibration or surging, a tentative design procedure using curve II (fig. 17) is suggested.

(4) Both graded and uniform materials are satisfactory for filters as regards holding a base material in place. Gap-graded materials and materials so widely graded that they tend to segregate during placement are not recommended.

(5) If, for any reason, there is doubt concerning the applicability of the above criteria, laboratory tests are recommended for determination of final design.

(6) For sands having idealized gradations and the same D_{15} size, the greatest permeability occurred at a uniformity coefficient (C_u) of approximately 2.7, with lower permeabilities for C_u values less and greater than this value. The lowest permeabilities resulted when the C_u was greater than about 4.

The "fig. 17" referred to is the same as Figure 4 in this paper.

K. P. Karpoff (USBR)--1955

Karpoff (9), a materials engineer for the Bureau of Reclamation, conducted a study of design criteria for protective filters in the mid-1950's. The model testing apparatus employed 8 inch diameter transparent plastic cylinders as sample holders. The hydraulic heads used ranged between 2 feet and 30 feet for the series of tests. The study included filters made of both uniform and graded subrounded sand and gravels and crushed rock. Karpoff defined a uniform material as one having an approximate straight line distribution (no tails at extreme sizes or significance changes in slope) gradation curve, with the major particle size variation being limited to one to three particle size divisions (sieve sizes?) on the USBR gradation curve sheet. A graded filter material was defined as a "poorly" or "well-graded" material having a concave, convex, s-shape, or straight-line distribution gradation curve.

Karpoff departs somewhat from the general use of the 85 and 15 percent grain sizes as indices for the criteria ratios. He suggested that the characteristics of a uniformly graded material result from the "degree of fineness, as represented by the mean grain size, which is approximately represented by the D_{50} grain size". For natural or protected soil Karpoff suggests that the mean grain sizes are between 40 and 60 percent, thus d_{50} size was used as an index. For graded filter materials, the degree of fineness, the range and shape of the gradation curve, and the skewness of the curve toward the fine or coarse sizes were considered as characterizing the materials. Because of the more complicated characteristics of graded materials Karpoff concluded that it was necessary to specify two definite points for ratio criteria between the soil and the filter material. A study of filter gradation curves for materials used in the study indicated that the mean grain size ranged between the approximate sizes of 40 and 60 percent (as defined by percent passing). Therefore an average size of 50 percent passing was chosen as one point and the 15 percent passing size was arbitrarily selected as the second point, since it was believed that the finer grain sizes affected permeability and particle movement.

The criteria resulting from the study were adopted by the USBR for the design of protective filters. The criteria for subrounded materials are as follows:

$$\text{Uniform Grain-Size Filter: } \frac{D_{50}}{d_{50}} = 5 \text{ to } 10$$

$$\text{Graded Filters: } \frac{D_{50}}{d_{50}} = 12 \text{ to } 58; \quad \frac{D_{15}}{d_{15}} = 12 \text{ to } 40$$

Graded filters should also met the following:

a. Filter material should pass the U.S. Bureau of Standards 3 inch screen, to minimize segregation and bridging during placement,

b. To prevent the excessive movement of fines into the filter or into drainage pipes, the filter material should not contain more than 5 percent of minus U.S. No. 200 sieve material,

c. The gradation curves of the filter material and the protected soil should be approximately parallel in the range of finer sizes, since the performance of the filter is dependent on the "skewness" of the filter gradation curve toward the finer size particles, which give support to the fines in the soil,

d. The maximum size of the perforations or joint openings in collector (underdrain) pipes should be one-half of the D_{85} of the filter material (Karpoff reported that this criterion had proved satisfactory in all filter tests conducted in the laboratory), and

e. If the soil contains particles larger than U.S. No. 4 sieve size, the filter should be designed for the portion of the soil smaller than the No. 4 size.

For crushed rock filters, Karpoff stated that the studies did not provide sufficient data such that criteria could be developed for both uniform and graded filters. He labelled the crushed rock criteria as tentative. These criteria are as follows:

$$\frac{D_{50}}{d_{50}} = 9 \text{ to } 30; \quad \frac{D_{15}}{d_{15}} = 6 \text{ to } 18$$

Karpoff noted that all filters designed by the adopted criteria were "stable in all respects". He stated that filters "designed outside the coarse limit shown by this paper, but within the coarse limit of the other criteria showed a visible instability". The "other criteria" Karpoff refers to are those developed by Bertram (3). Karpoff also observed that a D_{15}/d_{85} ratio of 4 for particular cases was too high.

Criteria Currently Used by Corps of Engineers

The following criteria are found in part or entirely in a number of Corps' design manuals (15) (16) (17) (18) (19).

Stability or Piping Criterion:

$$\frac{D_{15}}{d_{85}} \leq 5$$

If crushed rock is used for the filter material the ratio of 5 may be too high and laboratory tests should be used to confirm design.

Permeability Criterion:

$$\frac{D_{15}}{d_{15}} \geq 5$$

Other Criterion:

$$\frac{D_{50}}{d_{50}} \leq 25$$

If the protected soil is a medium to highly plastic clay without sand or silt particles the D_{15}/d_{85} and D_{50}/d_{50} criteria may require a multi-layer filter structure. For clay soils the D_{15} size may be as large as 0.4 mm and the D_{50}/d_{50} criterion may be disregarded. This relaxation of criteria for clays will allow the use of a single layer filter in most cases, but the filter should be well-graded and should have a coefficient of uniformity (C_u) of 20 or less to prevent segregation of the filter material. Cohesive soils have an inherent resistance to piping because of their cohesive property and tensile strength.

Collector Pipe Criteria:

Slots (rectangle or square): $$\frac{D_{85}}{\text{Slot Width}} > 1.2$$

Circular Holes: $$\frac{D_{85}}{\text{Hole Diameter}} > 1.0$$

Porous Concrete: $$\frac{\text{15 percent size of aggregate in pipe}}{D_{85}} \leq 5$$

The criterion for porous concrete pipe is conservative and is used since no proven criterion is available.

CHAPTER IV

MAJOR FILTER APPLICATIONS

General Applications

Mineral aggregate filters, when properly designed and constructed, can provide permanent security against the damaging effects of seepage through soils. Filters are generally used to intercept the seepage flow, collect it, and discharge it through either the filter media itself or through an internal (buried in the filter) drainage pipe. Filters of some form are used in various ways, ranging from the control of seepage through multi-million dollar earth dams to draining agricultural land.

Earth Dam and Levee Applications

Filters are of major importance in seepage control in earth dams and levees. The filters may have a number of shapes and locations within the earth structure. A prime example of the use of a filter is the so-called "chimney drain" illustrated in Figure 5(a). The chimney may be either inclined, as in the illustration, or vertical. Based on the writer's experience, the cross-sectional width should be around 10 feet (minimum). This dimension must, for practical reasons, be compatible with construction equipment. Too narrow a width, while satisfactory from the viewpoint of seepage control, could complicate the actual chimney construction. The outlet for discharge may be a downstream horizontal continuation of the chimney with a toe drain. Tl horizontal portion may be continuous for the length of the chimney or may have a "finger drain" configuration, depending on the expected discharge or other considerations, such as topography.

The filter configuration illustrated in Figure 5(b) will, in the writer's opinion, have limited application. However, one excellent example would be where excessive seepage was expected along an interfac between embankment and in situ foundation soil. The filter would then run longitudinally the length of the embankment. The collector drain pipe could be either perforated or have open joints, depending on the filter design.

Figure 5(c) illustrates the use of a filter with a rock toe. Base on observations by the writer, the applications of such a system are limited. In theory the rock toe should extend to a height that would intercept the line of seepage through the embankment. If the embankment was a homogenous mass, an accurate analysis of the seepage path would be possible. However, in practice, few if any, embankments ever approach a homogenous condition. All embankments are stratified to some degree because of the variations in soil properties, even for soils of the same classification. In addition, the lift method of constructing embankments affects stratification and particularly horizontal permeabilities, which in turn affect the seepage paths. If the upper limit (line of seepage) is not intercepted by the filter-rock toe, it is not effective and the stability of the embankment is endangered, as the upper downstream slope could become wet and/or eroded

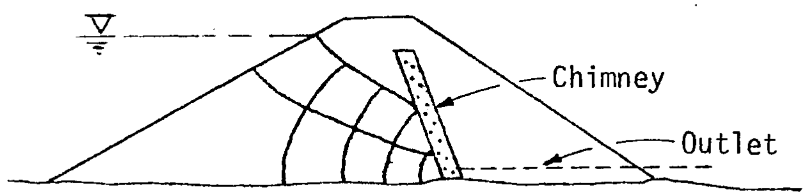
The writer can not see any instance, in which seepage control is required, that the chimney drain would not be preferred to a rock toe drain.

The upstream slope (reservoir side) of earth embankments requires protection from such hazards as wave erosion and floating ice or debris damage. One method of protection which is often used is to place a blanket of riprap (rock fragments) on the face of the upstream slope. A bedding layer or filter is required between the riprap and the embankment to prevent the fine grained soils in the embankment from moving into the riprap. In addition, the filter should be designed such that it will not pipe into the riprap. Because of the extreme differences between the void spaces in the riprap and the particle sizes of the embankment material, a multi-layer filter is often required. Filter layers should be a minimum of 8 inches thick (20). Figure 5(d) illustrates a slope protected by riprap with a filter.

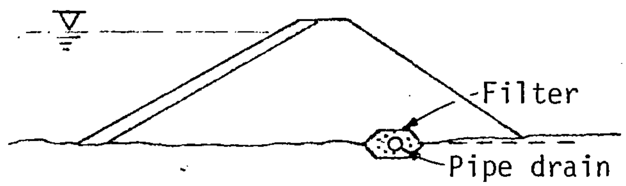
Airfields

For satisfactory performance the substructure of paved surfaces many times requires that the base course and subgrade be drained of surface infiltration and/or groundwater present in pervious in situ strata.

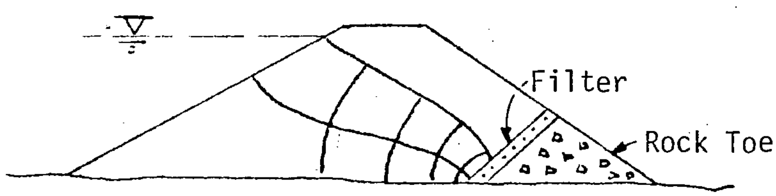
For airfields, the Corps (15) breaks subdrainage into three categories; base, subgrade, and intercepting. As a general guide the requirements for base drainage, where the base is subject to inundation may be determined from the following tabulation:



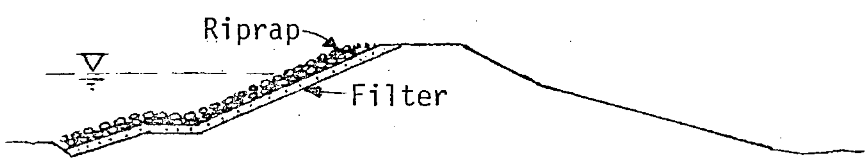
a) Chimney Drain



b) Longitudinal Filter with Collector Pipe



c) Rock Toe with Filter



d) Riprap with Filter

Figure 5. Typical Filter Uses for Earth Dams (After Cedergren, 2)

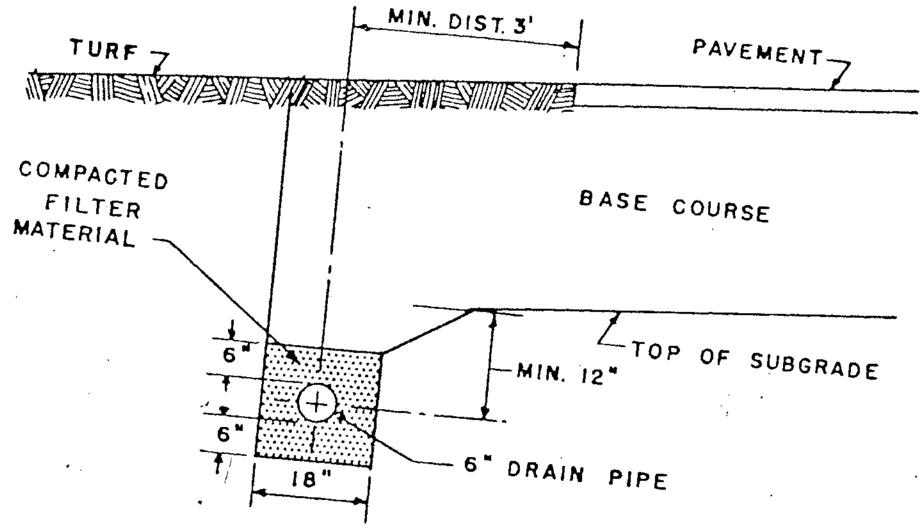
TABLE II

BASE DRAINAGE REQUIRED IF SUBGRADE PERMEABILITY LESS THAN LISTED VALUE (After Corps, 15)

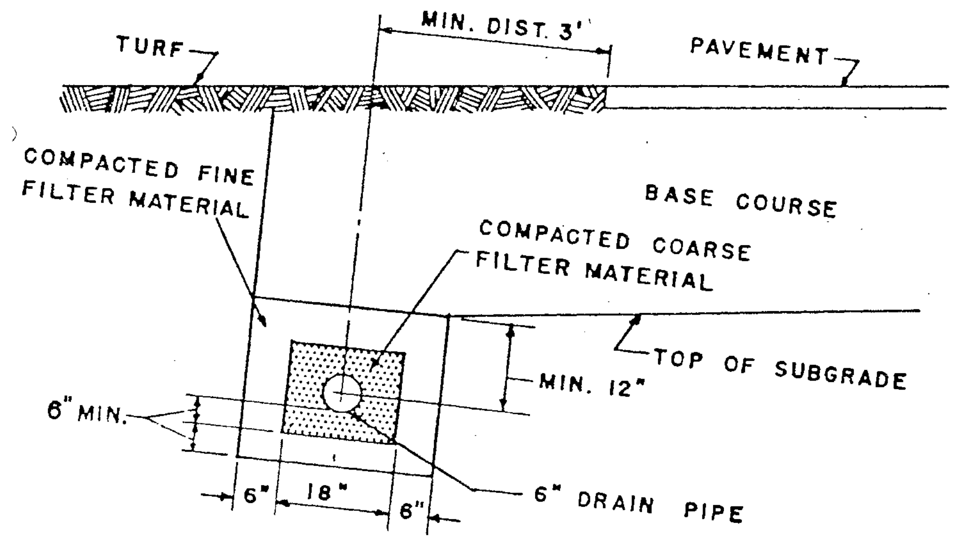
Depth Groundwater (ft)	Permeability (K) (ft per min)
< 8	1.0×10^{-5}
8 to 25	1.0×10^{-6}
> 25	1.0×10^{-7}

The subgrade should be drained if seasonal fluctuations in the groundwater level rise in the subgrade to within one foot below the bottom of the base course. Similarly, if seepage through pervious zones may be expected to affect the local elevation of the groundwater such that groundwater will rise to within one foot of the bottom of the base course then an interception drain should be installed to intercept the seepage flows. Figure 6 illustrates a typical base drain, Figure 7 illustrates a typical subgrade drain and Figure 8 shows a typical interceptor drain.

The term "drain" refers to a filter with a perforated, porous or open joint collector pipe. The pipe bedding (filter material) should be a minimum of 6 inches in depth. The total cross-sectional area of discharge pipes should be adequate to carry the maximum inflows expected. In areas where frost penetration must be considered in the design, the depth of cover over the pipe (to the center line of pipe) should be at least the depth of frost action.



a) One Gradation of Filter Material



b) Two Gradations of Filter Material

Figure 6. Typical Details of Base Drain Installations (After Corps of Engineers, 15)

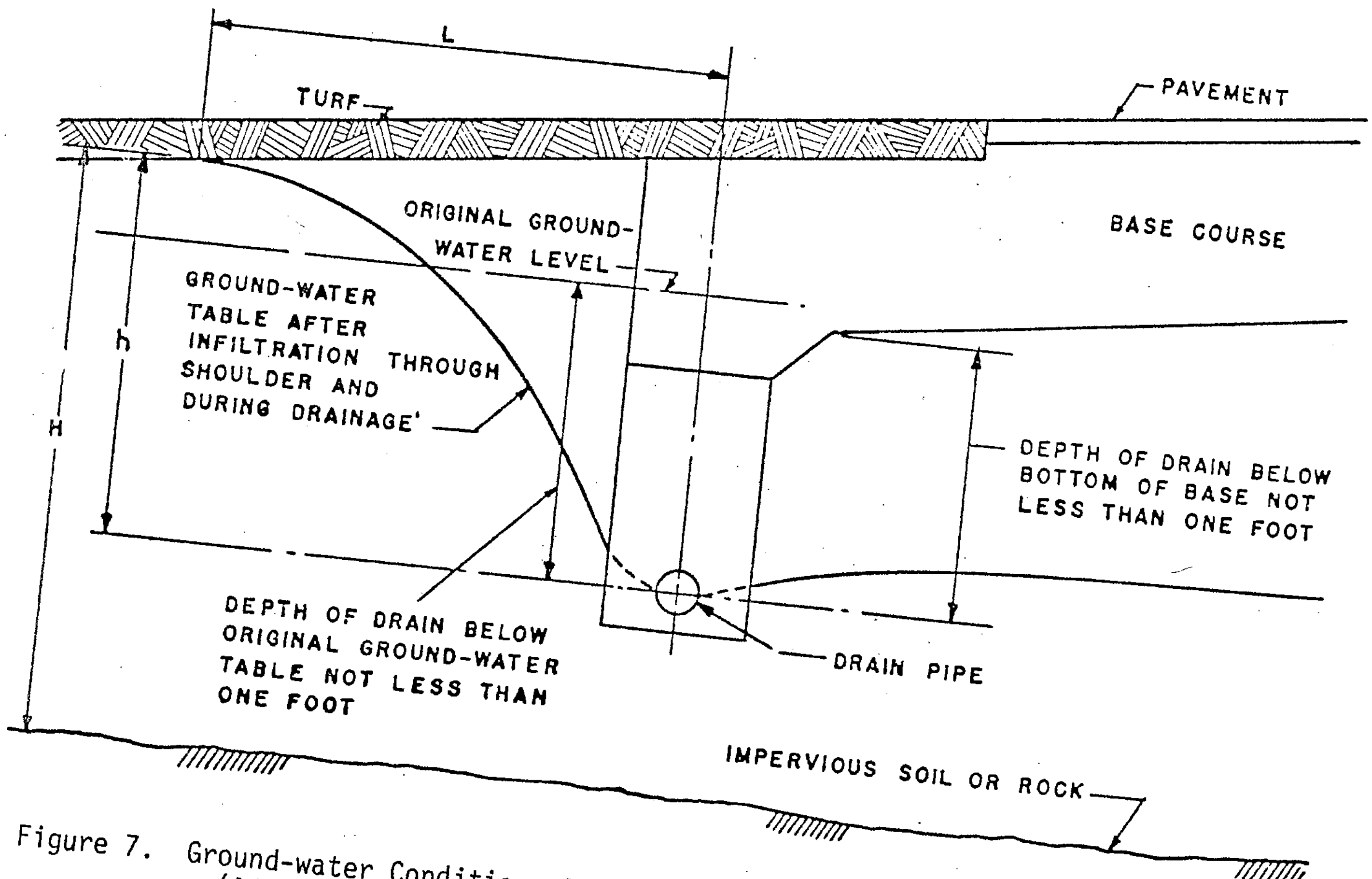


Figure 7. Ground-water Conditions After Installation of Subgrade Drainage (After Corps of Engineers, 15)

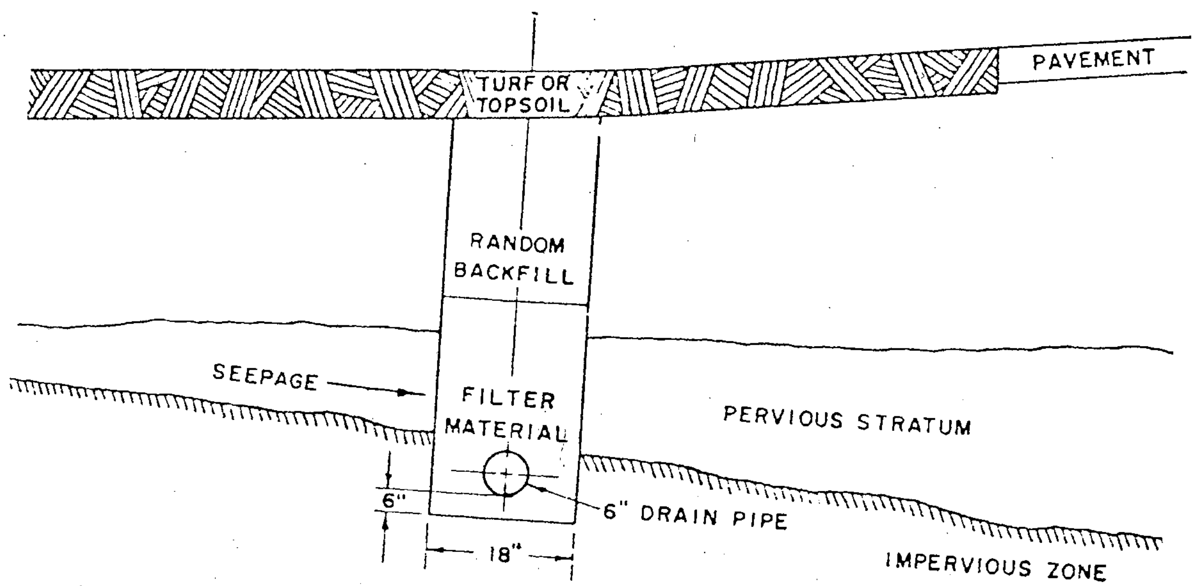


Figure 8. Typical Installation of Intercepting Drains (After Corps of Engineers, 15)

The permeability of the base course plays an important part in the complete design. The referenced Corps' manual (15) suggests coefficients of permeabilities (K) for remolded (compacted) sand and gravel as follows:

TABLE III

AVERAGE COEFFICIENTS OF PERMEABILITIES (K)
FOR REMOLDED SAND AND GRAVEL
(After Corps, 15)

Percent by Weight Passing 200 Sieve	K - Remolded Samples (ft per min)
3	10^{-1}
5	10^{-2}
10	10^{-3}
15	10^{-4}
25	10^{-5}

The permeability K of crushed rock without many fines will generally exceed one foot per minute. For uniformly graded sands, the K value may be 4 times as large in the horizontal direction (parallel to compaction planes) as values resulting from laboratory tests on remolded (compacted) samples. For other materials the difference may be as great as 10. Table IV suggests values of K for sands and sand-gravel mixtures. In addition, the Table suggests methods (laboratory or indirect methods) for determining K values. If the base is composed of several layers of different materials a reasonable weighted value of K may be obtained from the following equation:

TABLE IV

PERMEABILITY CHART (After Corps of Engineers, 15)

"k" in cm. per sec. (Log Scale) (1 cm./sec = 2 ft./min.)

10^{2} 10^{1} 1.0 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9}

DRAINAGE PROPERTIES	Good Drainage		Poor Drainage	Practically Impervious
	Drains Very Rapidly	Drains Rapidly	Drains Slowly / Drains Very Slowly	Drainage Imperceptible
SOIL CLASSIFICATION	GW-SW	GP-SP	ML-OL, GF-SF-MH / GC-SC-CL	CL-GH-OH
TYPES OF SOIL	Clean Gravel	Clean Sand, Clean Sand and Gravel Mixtures	Very Fine Sands; Organic and Inorganic Silts; Mixtures of Sand, Silt, and Clay; Glacial Till; Stratified Clay Deposits; etc.	"Impervious Soils" e.g. Homogeneous clays below zone of weathering
			"Impervious Soils" which are modified by the effects of vegetation and weathering	
DIRECT DETERMINATION OF COEFFICIENT OF PERMEABILITY	DIRECT TESTING OF SOIL IN ITS ORIGINAL POSITION (e.g. Well Points) Reliable if properly conducted. Considerable experience required			
	CONSTANT HEAD PERMEAMETER Little experience required			
	TURBULENT FLOW FOR HYDRAULIC GRADIENTS LARGER THAN TEN	FALLING HEAD PERMEAMETER: Reliable Little experience required	Unreliable Much experience necessary for correct interpretation	Fairly Reliable Considerable experience necessary
INDIRECT DETERMINATION OF COEFFICIENT OF PERMEABILITY	COMPUTATIONS From grain size distributing, (e.g. Hazen's Formula). Applicable only to clean cohesionless sands and gravels			
		HORIZONTAL CAPILLARITY TEST Very little experience necessary. Especially useful for rapid testing of a large number of samples in the field without laboratory facilities		COMPUTATIONS From consolidation tests. Expensive laboratory equipment and considerable experience required

10^{2} 10^{1} 1.0 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9}

$$K = \frac{K_1 d_1 + K_2 d_2 + - - - - - - + K_n d_n}{d_1 + d_2 + - - - - - - + d_n}$$

Where K = weighted value for entire base course structure (ft per min)

K_n = value for n layer (ft per min)

d_n = thickness of n layer (ft).

The design of a subdrainage systems which uses internal collector pipes should have provisions for checking the performance of the system at given points in the system. This may be accomplished by requiring manholes, observation basins, or capped risers at key points in the system. These features would also permit the system to be flushed, if required during the system life.

An excellent paper by Casagrande and Shannon (21) deals with general base course saturation problems and their analyses.

Highways

Seepage, surface infiltration, and groundwater control via mineral aggregate filters for highways require the application of design procedures similar to those used for airfields. In the writer's opinion, both types of structures involve the same considerations and design methods. In practice, highways offer more challenge to the designer. Highways, because of their length, encounter a myriad of terrain, soil, and groundwater conditions generally not encountered in an airfield facility. Highways constructed on the sides of hilly terrain are particularly susceptible to damage from both surface and subsurface water. In areas where groundwater conditions are severe, highways can not be expected to perform adequately without proper subsurface drainage.

Lovering (22) states that with the present day trend toward the elimination of side ditches, wider lanes, and paved shoulders, the need for properly designed subsurface drainage has become more demanding. He further suggests that while culverts are selected with great care to insure adequate capacity for surface runoff, the subsurface drainage system is designed with little consideration as to its required capacity. To illustrate, Lovering cites a hypothetical example where a one-foot thick filter placed on a sixty-foot wide section of saturated soil having a 2 percent slope (i = 0.02) toward the underdrains and a K of 10 feet per day (similar to a gravel-sand mix) would be capable of carrying a little less than 3 gallons (0.37 cu ft) of groundwater to the underdrain per day. If the soil adjacent to the filter had a K of 0.2 feet per day (similar to an inorganic silt) and a slope of 4 percent (i = 0.04) the soil would try to yield approximately 3.6 gallons (0.48 cu ft) per day to the filter. It is evident that an excess of 0.11 cu ft exists which could result in an increase in hydrostatic pressure sufficient to lift the pavement and result in its failure.

Another interesting possibility pointed out by Lovering is when the permeability of a long continuous filter (as often found in highways) is reduced (because of segregation or minor changes in gradation of filter material). When the filter is filled to capacity, such reductions in permeability would act as checks or barriers to flow, resulting in an increase in head which in turn could result in excessive uplift, causing pavement failure. Lovering suggests closely spaced cross-drains or outlets to reduce length of flow. He suggests that the cross-drain (perpendicular to highway alignment) be cut after the filter and base have been placed. The cuts would insure that water would enter the cross-drains and not bypass them by flowing along compaction planes in the base or filter.

Other Applications

Mineral aggregate filters may be used to remove subsurface seepage and/or groundwater in most instances when it affects the function or integrity of a facility. The previously discussed examples are the major (with regard to size) applications, but filters are used to contr subsurface flows behind retaining walls, to intercept groundwater around building perimeters, and in the development of some wells. In all cases each application must stand on its own and the criteria must be used in an analysis suited to the conditions.

Filter Economics

Cedergren and Lovering (24) and Cedergren (23) have conducted studies into the use of layered filters, based on economics. Cedergren (23) cites an example where a large dam had an internal drainage system whose cost represented 15 percent of the project cost. Under full head the system had a discharge capacity of 3 gallons per minute. The cost per gallon per minute of discharge capacity was over $15,000. A simila example was a highway drainage system which had a gallon per minute capacity cost of $50,000. Both structures suffered damage because of inadequate drainage capacity of the systems. Cerdergren (23) suggests the low capacities resulted from the filters being "pre-clogged" by their own fines. Both papers (23) (24) suggest the use of a layered or "sandwich" type filter structure, where a coarse (one-sized gravel or rock) is enclosed by enveloping layers of finer material which would prevent piping of the protected or water-bearing soil. This filter structure would be required where an appreciable quantity of seepage is to be removed. The inner layer of rock or gravel, called the "conductor or conveyor," would serve as the flow channel for the seepage. In the writer's opinion it would act and serve the same purpose as a collector pipe. For low quantities of seepage, a single layer filter should be adequate.

In the cost comparisons presented, the cost for conducting 1 gallon per minute of seepage a distance of 100 feet ranged from $90,000. for a single layer filter of washed concrete sand, high in fines, to $3.50 for a layered filter using 1 inch diameter gravel enclosed in "fine filter" (23) (24).

While the studies fail to make a cost comparison with a system using a collector pipe as the "conductor" and surely do not reflect price differences in the cost of materials in different regions, they do strongly point out the possible advantages of multi-layer filters.

CHAPTER V

FILTER CONSTRUCTION

General

Cedergren (2) emphasizes the extreme importance of filter specifications and good construction practice when he states, "No other single feature of many civil engineering works is more vital to long, trouble-free performance than the drainage features. The need for high quality workmanship in the construction of drains cannot be overemphasized. Well written, enforceable specifications are a prerequisite for good quality construction." Regardless of how good the laboratory testing results or how detailed and comprehensive the analysis and design, if proper specifications and construction practices are not used the filter can be completely worthless and even a danger to the structure.

Specifications

Specifications generally do not deal with the physical dimensions of the drain or filter. Such details as thickness, width, slope, and location are presented in a set of contract plans prepared in conjunction with the specifications. The major aspects covered in the specifications are type of material (quality) to be used (sometimes a particular source of the material is specified), the gradation(s) of the material(s) the method and degree of compaction, laboratory tests required (for material quality and final compaction), and the control the project engineer has over the contractor's operation.

The material to be used in the construction is of paramount importance. From the view point of economics, using material available on-site is preferred. However, naturally occurring sands and gravels vary widely in gradation within a given borrow area. They are often stratified with an individual stratrum containing significant differences in percent fines (or coarse particles) and may be inter-bedded with clay or silt strata. Removing overlying overburden deposits must be accomplished with care or the underlying sand and/or gravel may become contaminated. Natural deposits must be explored through drilling to prove they are adequate, both in quality and quantity. The design engineer must be satisfied through exploration and testing (generally compaction, gradation, and permeability is required) that the amount of borrow is sufficient for the proposed drainage system and that the values used to design the filter accurately represent the borrow material. Natural deposits may often require washing and/or screening to develop the required gradation.

Specifications are often inconsistent with intent. They are vaguely worded, contain omissions, and are generally unenforceable. Specifications should avoid general terms such as pervious or free draining unless specifically tied to requirements for gradation, soundness, and permeability in a manner that will insure that the desired physical properties are obtained (2). When particular gradations are required the "time and place" of sampling and testing should be clearly defined in the specifications since many aggregates will break down (producing a great percent of fines) due to abrasion during excavation, hauling, placement, and compaction (2). The methods of testing should also be specified (ASTM, etc.) and should be consistent with methods employed during design. The method of compaction (type of equipment to be used) and the type tests to be used to measure in place densities (Standard Proctor, relative density, etc.) should be specified.

Cedergrene (2) cites an example of a specification which resulted in an inadequate structure.

> A gravel drain shall be constructed in the downstream portion of the embankment to the lines, grades, and dimensions shown on the plans, or as directed by the Engineer in the field. The gravel shall be clean, well graded, free draining and contain no cobbles greater than 6 inches in diameter. Suitable gravel is available in the banks of the river from ____ to ____ feet downstream from the center of the dam, but some care in selecting the gravel may be required to insure its being clean and free-draining.

Cedergren points out that the only firm control the project engineer had over the material used for the filter was to limit its maximum particle size to less than 6 inches with all other requirements reduced to a matter of opinion. As a result the contractor was careless in developing the borrow area and the material to be used in the filter was contaminated with excessive percentages of overburden (clay and silt), resulting in a filter that was impervious. Cedergren (2) points out the extreme difficulty in writing specifications that will cover every minute detail. He suggests that "a reasonable level of integrity on the part of the contractor must be assumed". The writer has reasonable doubt as to the validity of such an assumption. Cedergren (2) offers an example specification that would produce a satisfactory job as follows:

The aggregate used shall be composed of hard, durable mineral particles free from organic matter, clay balls, soft particles, and other impurities or foreign matter. When tested by Test No. ___, when sampled after being compacted in the work, the material shall conform to the following grading requirements:

Sieve No. or size	Percent passing by weight
1 1/2 in.	100
3/4 in.	50 to 100
No. 4	20 to 40
No. 16	7 to 20
No. 50	0 to 5
No. 100	0 to 2

Drain gravel shall be placed with spreader boxes or other approved equipment in horizontal lifts not over 12 inches in thickness before compaction. To minimize segregation and to facilitate its compaction, the material shall be thoroughly saturated at the time of its placement and compaction. Each lift will be compacted with ______ passes of a ____ roller weighing ____ lbs per linear foot.

The material as placed and compacted in the work shall be free of segregation and free of all contaminating materials. If unsatisfactory materials, or contamination are permitted in the work, the unsatisfactory materials shall be removed to the satisfaction of the Engineer and replaced with acceptable materials at no additional cost to the owner.

The drain shall always be maintained at least 12 inches above adjacent embankment zones. At no place shall the dimensions be smaller than those given in the drawings or stated in the specifications. Equipment crossovers shall be limited to not more than two at any given level of the embankment. Each crossover shall be cleaned of all contaminating materials to the satisfaction of the Engineer and approved by the Engineer before additional drain materials are placed in these areas.

In cases of dispute over the acceptability of any portion of the placed materials, referee samples weighing 100 lbs shall be secured by the Engineer for testing. If such a sample fails to meet the specification requirements, all of the material represented by the sample shall be considered unacceptable and shall be removed to the complete satisfaction of the Engineer.

The Corps of Engineers generally defines the requirements of the filter material as "well graded between the prescribed limits" and that it "shall be composed of tough, durable particles, shall be reasonably free from thin, flat and elongated pieces, and shall contain no organic matter nor soft, friable particles in quantities considered objectionable by the Contracting Officer." One manual (16) states that it is imperative that the gradation of the material be closely controlled to meet the requirements resulting from the design and that while the des criteria may appear restrictive in some instances, "The importance of filters does not permit any wide deviation."

Construction

After having obtained a suitable material for the filter several additional important aspects of construction still remain. The major items of concern requiring control are the placement and compaction of the filter material. Extreme care should be exercised in the placemer of the material to avoid segregation of the material. Filter materia generally mixtures of sand and gravel, are particularly susceptible tc segregation of particle sizes. Segregation can occur during hauling the material is subjected to bumps and jarring from rough roads or ma occur if "worked" excessively during placement by "blading" back and forth. It should be placed in uniform layers at the required loose lift thickness. Proper compaction will minimize the possibility of t migration of fines, both during construction and the life of the filt

Most filter material would be considered cohesionless. In the majority of cases either standard or modified proctor densities are meaningless for cohesionless material, particularly if clean (free of excess fines) as most materials for filter use should ideally be. The required density for compacted filter sands and/or gravels should be based on laboratory relative density tests. The Corps of Engineers generally requires that cohesionless fills be compacted to an average relative density of 85 percent with a minimum relative density of 80 percent allowed.

Cohesionless materials may be best compacted by steel-wheel vibratory rollers. Rubber-tired rollers may also give acceptable densities.

The Bureau of Reclamation, USDI lists several important compaction factors to consider in its 1960 Earth Manual (25). The reader will note that the percent relative density required by the USBR differs from the Corps of Engineers requirement. The USBR gives the following guides for filter construction:

(1) The subgrade before filter placement should be firm and, if necessary, be lightly tamped or rolled.

(2) Clean filter material should have sufficient water content (3 to 10 percent) during placement, and the placement method should be such that segregation is prevented.

(3) Thin filters are usually firmly compacted with light flat rollers, or are tamped to a firm condition. Unless otherwise specified, thick filters are compacted to 70 percent relative density in a manner similar to free-draining sand-gravel backfill to prevent settlement.

(4) The filter layers for coarse filter material (3-inch maximum size) are usually not less than 8 inches in thickness, and layers of finer filter material are often of 6-inch minimum thickness. However, for severe field conditions such as high head, variations in base material, or filter gradations which are near the extreme coarse limit, the minimum thickness of 8 inches may be specified. For zoned filters these minimum thicknesses may be specified and are maintained for each layer.

(5) Where drainage pipe is used in a filter system, the capacity of the pipe should be sufficient to collect the seepage water and to conduct it to a place of discharge.

(6) While the pipe is being laid, the openings are often protected from inflow of fines of the filter material by burlap or other suitable permeable material.

The above guides appear to have been adopted from the experimental work by Karpoff (9). Karpoff recommendations are given below for comparison:

1. The subgrade before placement of filter material has to be slightly compacted by means of a light roller, or by other suitable compaction equipment and smoothed with a light flat roller or pneumatic roller. These measures are necessary for filling depressions and holes that might cause unequal settlement of a drain.

2. The clean filter material should have sufficient moisture content (3 to 10 per cent) during placement to prevent segregation.

3. The filter material should be compacted in about 4-in. layers with light flat roller or, where space is limited, by hand tamping.

4. The filter layer should not be less than 8 in. in thickness. Where the subgrade consists of fine-grained soil a "zoned" or two-layer filter is usually required and the combined thickness of both layers should be at least 16 in.

5. The filter system must be sufficiently thick to act as an insulator where frost action is involved.

6. Where drainage pipe is used in a filter system, the capacity of the pipe should be sufficient to collect the seepage water and to conduct it to a place of discharge.

7. The size of the perforation and joint openings in the drain pipe should be made with consideration of the filter material as follows: Maximum opening = 1/2(85 percent size FM).

While the pipe is being laid, the slots should be protected from inflow of fines of the filter material by burlap or other suitable permeable material.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

General

This report is a study of the development and present state-of-the-art of grain-size criteria for mineral-aggregate filter design. Drainage systems using mineral-aggregate filters are used frequently to control the seepage of water in foundations and earth structures. Earth dams, levees, and highways make extensive use of such drainage systems.

All too frequently, the design engineer either devotes too little time to the proper analysis, design, and specifications of the filter system or does not completely understand the principles involved. As frequently, the techniques employed in the construction of filters result in a system that is inadequate or completely non-functioning.

The concept and construction of a properly functioning filter suited to the problem requires, probably, more than any other single feature of a total structure, close attention to each phase of its development. Such a strong emphasis can be justified by simply remembering that water is "Public Enemy No. 1" to the civil engineer. Many structures, otherwise well designed, have failed or sustained serious damage because the possible effects of water were forgotten or not properly considered in both the design and construction stage.

Conclusions

The design and construction of drainage systems utilizing mineral-aggregate filters may be separated into six major phases as follows:

1. Determine if a seepage problem exists: The designer may become aware of the presence of a problem in a number of ways. Site exploration via foundation drilling is an important source of data. Past history or design experience of the area is often a source of data. Certain structures, by their very nature, inherently have seepage problems. An example is an earth dam. By whatever methods available the designer must ascertain the problem.
2. The analysis of the soil: Once the existence of a seepage problem is established the designer must now begin to define all the parameters required for its solution. The properties of the water-bearing soil to be served by the filter should be obtained by laboratory testing if possible. Most important are the soils grain-size distribution (gradation) and permeability (both horizontal and vertical). Very generally, the soil will be one of two major types--cohesive or cohesionless. The type will affect the application of design criteria. If both types (or a single type having very different gradations and permeabilities) are present the filte must be designed to hold the one having the smallest particle sizes but also the filter must be sized to handle the combined flows (cohesive soils will generally have the smallest particle size but the cohesionless soils will have the largest permeability and hence greatest inflow).

3. The analysis of the filter material: Frequently, the designer will and should try to use natural material located on or near the site. To do so, the quantity and quality of the material must be determined. The quantity must be ascertained in the field by exploration methods which most often involve drilling. When drilling is used care should be exercised in the proper logging and field classification of stratum thickness, and the depth of the water table (borrowing below the water table is not very economical). Bulk samples (bag) should be taken of suitably appearing aggregates for laboratory testing (compaction, gradation, permeability and strength). The testing will confirm their suitability (or non-suitability) and furnish data for design. If natural deposits are not available then commercial sources must be located. Again the suitability of the material must be determined and the data required for design obtained.
4. The design: In this step three paramount questions must be resolved--the location and configuration of the drainage system; the design of the filter (gradation); and the dimension (thickness) of the filter. The location and configuration are entirely dependent on the nature of the structure and the extent of the problem. Several major types of drainage systems are discussed in Chapter IV. The design of the filter generally refers to the design of a gradation based on grain-size criteria. Filter gradation may be broadly classified as either uniformly graded or well-graded. Each type may have different grain-size criteria and methods of application, depending on the nature of the soil to be protected and which criteria are being used. The designer may be limited to certain

criteria by the agency he works for or may choose the criteria that seem best suited to the problem. Regardless, the designer should exercise judgement in the use of the criteria. As previously discussed the design of a filter by grain-size criteria will not fix its dimensions (thickness or cross-sectional area). Cedergren (2) offers two approaches--assuming a thickness and solving for the required permeability to handle inflows or, given a permeability, solve for the required thickness. The writer prefers the latter approach. Both approaches are discussed in the Appendix. The single most important aspect of the sizing calculations is the correct determination of the quantity of seepage to be handled by the drainage system. Flow nets (also discussed in the Appendix in a limited manner) are useful in quantity studies.

5. Specifications: Properly worded specifications are essential to insure that good construction particles are used. Specifications are discussed in Chapter V.
6. Construction: Regardless of how thorough the design and its associated functions, without close control on the construction of the drainage system, and in particular the filter, the end product may be worthless. In fact the structure might be better off without the system if it does not function properly. The primary areas of concern are the filter aggregate, and methods of placement and compaction. The project engineer should be aware of the importance of the drainage system and its filters and should be armed with specifications that give him adequate control over the construction processes.

In the above outline of filter design and construction no single step can be singled out as the most important. Each is as important as the next and each must be properly handled.

One item that should perhaps be included as a seventh step is a post-construction inspection starting when the filters and drainage systems first begin to function and continuing throughout their service life. Discharges should be checked to see if they are clear or cloudy (indicating suspended fines). The quantity of discharge should be notec and perhaps checked against design estimated. If a collector pipe(s) is part of the system the amount of silting should be observed through inspection ports or manholes. Careful periodic inspections will dicate if any repairs or maintainance are required.

Recommendations

It is difficult to separate conclusions from recommendations. Base on the material covered in this report the writer has concluded that certain facts and various criteria appear logical to him and he would therefore recommend their use. Also, in the writer's opinion, general recommendations on the subject of filters may be misleading. However, based on the writer's experience and observations, several points worth listing are as follows:

1. All grain-size criteria should be used with caution. No given criteria will satisfy all conditions. Invariably the experimental studies compromised their recommended criteria with suggestions that laboratory testing might be required to prove the suitability of given filter designs. Properly understood and used criteria will in most cases, result in a suitable filter design. The choice of

which criteria to use must rest with the designer and the circumstances of the particular problem.

2. All filter designs should include an analysis of the quantity of seepage to be collected and discharged by the drainage system. In many cases the designer assumes, either on past experience or intuition, that a certain cross-sectional area is adequate. The result of such an assumption may be failure of the structure.
3. Multi-layer filters should be given more consideration in the design phase. There is sufficient evidence that they are often more efficient and economical than single stage filters.
4. Open-jointed collector pipes appear to be risky, Perforated pipes (underside only) appear to be more nearly satisfactory.
5. Close attention should be given to insure that specifications for filters are properly worded. Good specifications are needed to insure good construction.
6. Additional research is required. Several studies covered in this report admitted that certain recommendations were based on too little data or that certain conditions were not investigated because of the lack of time. Most studies were restricted to filter materials having uniform gradations. Non-uniformly graded materials deserve more study. Most studies seem directed at proving the validity of existing criteria rather than at developing new concepts. A new approach may be in order.

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APPENDIX

DESIGN EXAMPLES

Filter Design Using Grain-size Criteria

Design Data, General

All filter criteria are expressed, in one manner or another, in terms of the diameters of certain key percentages (percent finer by weight) of the grain sizes present in the filter material and the soil. The key diameters of the soil must be obtained from laboratory grain-sizes analyses conducted on representative field samples. Often the design is to determine whether a certain proposed material is acceptable as a filter material. In this case a grain size analysis must be made of the proposed material also. Many times the design calculations are to determine the diameters of the dey percentages of the filter material required to meet the criteria. In this case the gradation of the filter material is based on the calculations and a material must then be found that has the desired gradation (it may be a naturally occurring material or one that is manufactured).

Example Problem

The case where both the gradation of the soil mass [clayey sand (SC)] and the proposed filter material [naturally occurring poorly grade sand (SP)] are known is used in the following example problem. A number of gradation curves resulting from laboratory testing of representive field samples are shown for the clayey sand (SC) in Figure 9 and for the poorly graded sand (SP) in Figure 10. When given several curves for both the soil and the filter material, as is true in this case, th designer is faced with a choice of which values (diameters) to use in the design calculations. Average values could be used but a more logical approach would be to use the envelope developed by each family of curves. The envelopes have an extreme right and left hand value which, if properly chosen will insure the maximum safety in the calcul tions.

Piping Criterion (U.S. Army Corps of Engineers)

The objective of the piping criterion is to insure that the soil particles will not penetrate the filter. Therefore, the key diameter for the protected soil is taken from the right-hand side of its envelope, which represent the finer particle sizes. The particle size that will penetrate the filter is dependent on the void spaces in the filter. Therefore, the key diameter for the filter material is taken from the left-hand side of its envelope, which represents the coarser particle sizes and hence larger void spaces. The values for each are:

$d_{85} = 0.19$ mm

$d_{50} = 0.082$ mm

$D_{15} = 0.18$ mm

$D_{50} = 0.26$ mm

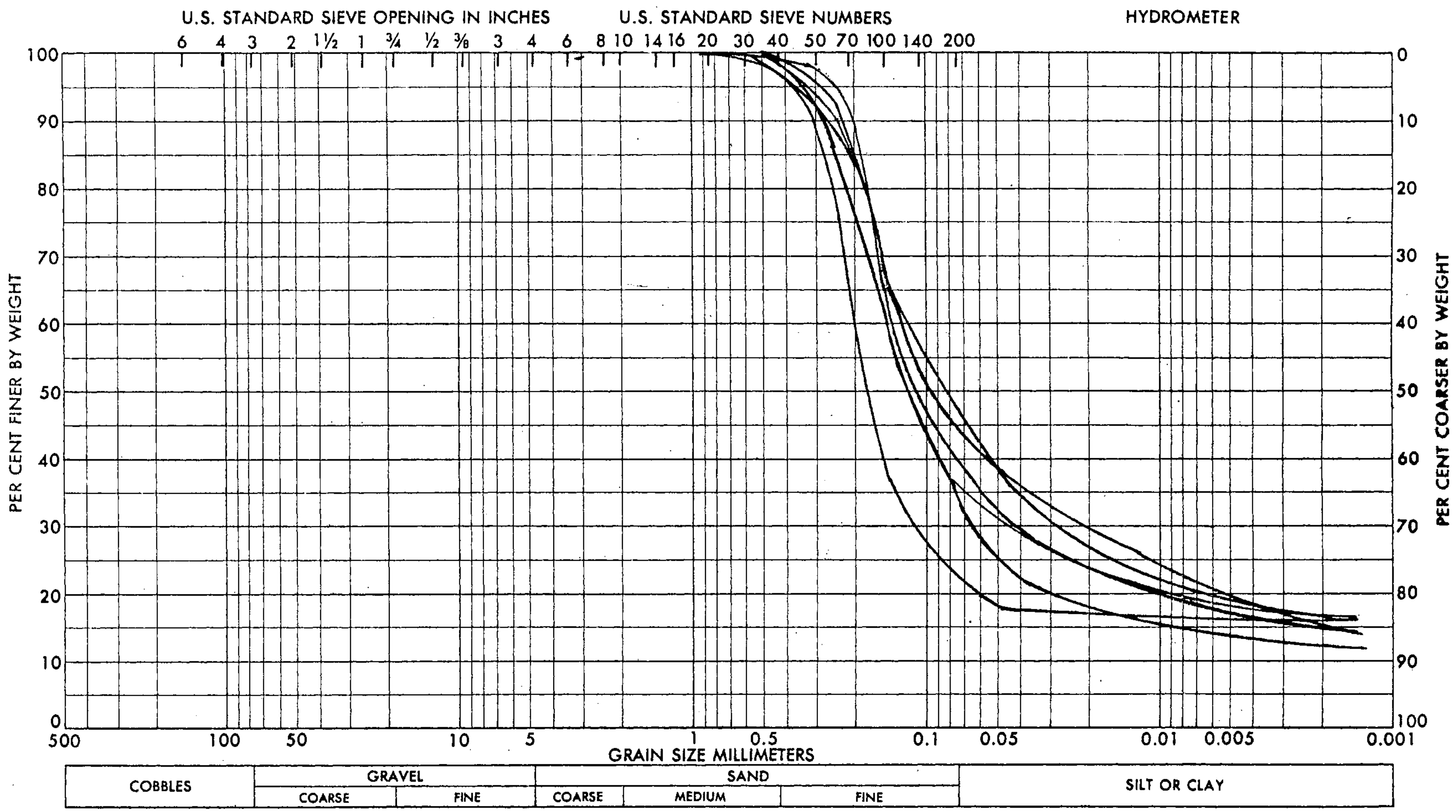

Figure 9. Gradation Curves for Soil

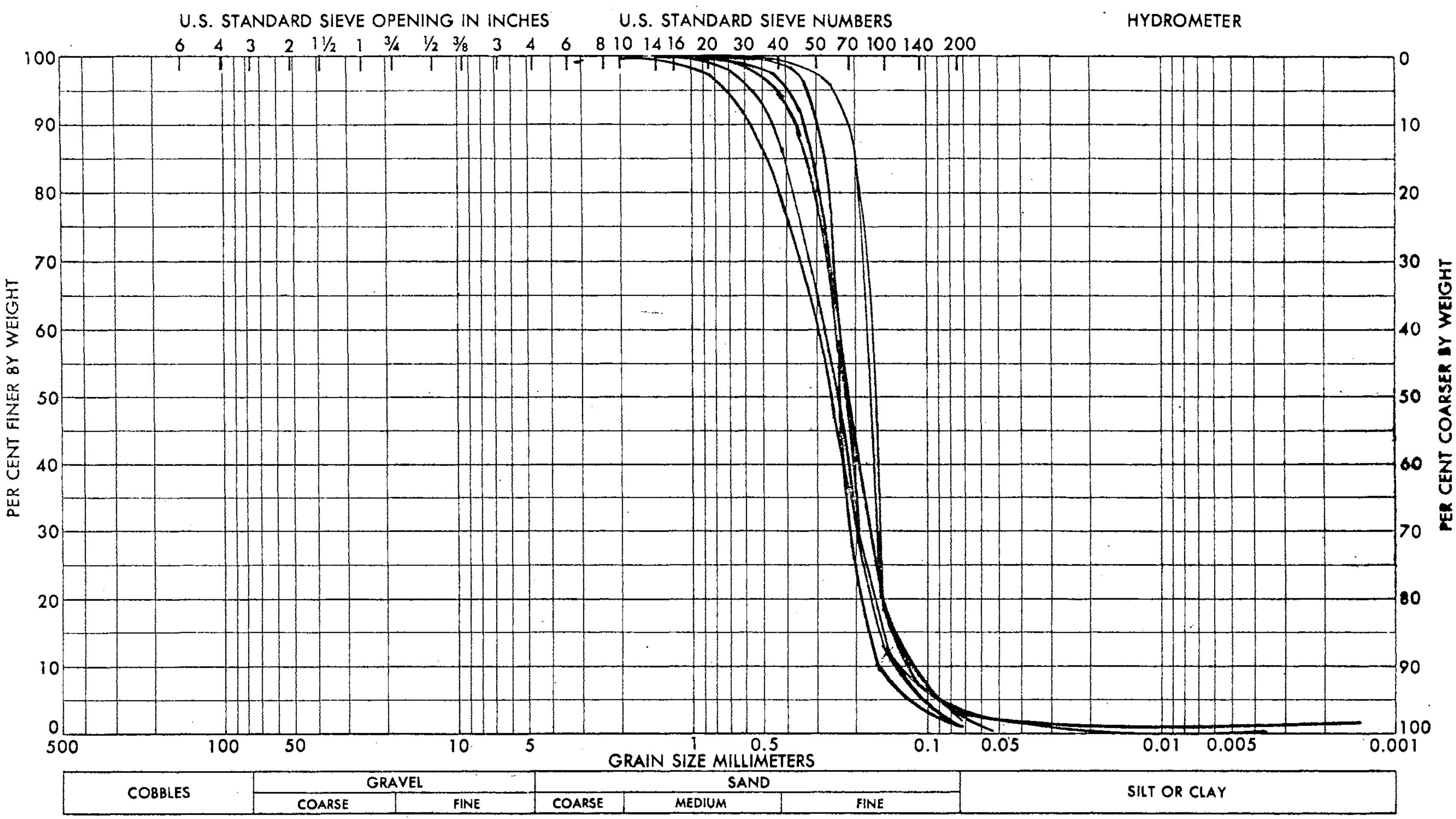

Figure 10. Gradation Curves for Filter Material

The piping criterion is:

$$\frac{D_{15}}{d_{85}} \leq 5$$

$$\frac{D_{50}}{d_{50}} \leq 25$$

The calculations give:

$$\frac{D_{15}}{d_{85}} = \frac{0.18 \text{ mm}}{0.19 \text{ mm}} = 0.95$$

$$\frac{D_{50}}{d_{50}} = \frac{0.26 \text{ mm}}{0.082 \text{ mm}} = 3.17$$

Both calculated ratios are considerably less than the miximum allowed values, so the sand (SP) is satisfactory as a filter material for the clayey sand (SC) with respect to the prevention of piping.

Permeability Criterion (U.S. Army Corps of Engineers)

The objective of the permeability criterion is to insure that the filter has sufficient permeability to carry the quantity of seepage collected from the water-bearing soil without detrimental seepage forces occurring in the filter. To use the envelopes for each material to best advantage, the diameters that will represent the largest permeability in the protected soil and the smallest permeability in the filter should be used. Therefore, data from the left-hand side of the soil envelope and the right-hand side of the filter material are used. The values for each are:

$d_{15} = 0.009$ mm

$D_{15} = 0.15$ mm

The permeability criterion is:

$$\frac{D_{15}}{d_{15}} \geq 5$$

The calculation gives:

$$\frac{D_{15}}{d_{15}} = \frac{0.15 \text{ mm}}{0.009 \text{ mm}} = 16.7$$

The allowable minimum of 5 is exceeded by a factor of over 3 therefore the filter material has adequate permeability to safely handle the seepage from the protected soil. The validity of the design is support by permeability tests on the involved materials. The maximum permeability observed for the soil was 0.88×10^{-4} cm/sec (horizontal) and the minimum permeability for the filter material was 16.7×10^{-4} cm/sec (vertical) which gives a difference in permeability of over 18.

Uniformity Coefficient (C_u)

Segregation of particles during placement is a major problem encountered in filter construction. Materials having a uniformity coefficient greater than 20 are said to show a marked tendency towards segregation (15). For the filter material used in this example the uniformity coefficient is:

$$C_u = \frac{D_{60}}{D_{10}}$$

Maximum D_{60} = 0.30 mm

Minimum D_{10} = 0.12 mm

$$C_u = \frac{0.30 \text{ mm}}{0.12 \text{ mm}} = 2.5$$

The segregation should not be great because of the lack of gradation f such a low uniformity coefficient.

Collector Pipe Design (U.S. Army Corps of Engineers)

If the drainage system included the use of perforated pipe buried in the filter to collect and discharge the seepage water, the followin criterion should be used:

$$\frac{D_{85}}{\text{Hole Diameter}} > 1.0$$

The largest allowable hole diameter would be:

D_{85} = 0.2 mm (from the finer or right-hand side of envelope for filter material)

$$\text{Hole Diameter} = \frac{0.2 \text{ mm}}{1} = 0.2 \text{ mm}$$

The hole diameter would have to be less than 0.2 mm to meet the criterion.

Similarly for slots:

$$\frac{D_{85}}{\text{Slot Width}} > 1.2$$

Slot width must be less than; $\frac{0.2 \text{ mm}}{1.2} = 0.17$ mm

Both of these dimensions for opening in collector pipes are not practical. The solution would be to use a double layer filter with the SP material against the soil (SC) and a gravel layer between the SP filter material and the collector pipe. A typical D_{85} for a fine gravel would be 3/8 in., which would allow a hole diameter in the collector pipe of something less than 3/8 in. The gravel layer would have to meet all grain-size criteria with regard to the SP filter material, as did the SP material with regard to the SC soil.

Filter Thickness

General Methods

As already discussed, the application of grain-size criteria to th design of a mineral aggregate filter only insures that the protected soil will not pass through the filter and that the filter has adequate permeability to prevent the build-up of large seepage forces in the filter. The criteria give no indication of the required dimensions (cross-sectional area) necessary to accommodate the quantity of water t be collected by and discharged through the filter. In other words, the filter should be "sized" similar to the way a pipe must be "sized", to carry a given quantity of flow.

Cedergren (2) (26) gives several reasonable methods of designing a filter for discharge capacity. He suggests that the capacity design may be made using Darcy's law, flow nets, or a combination of the two. Darcy's law has already been discussed previously. Cedergren (2) comments on the methods as follows:

> 1. Use Darcy's law both for approximating the rate of infiltration from the soil and for designing the drain, with the most reasonable values that can be assigned to:
> (a) The average or effective permeability of the soil formations which are to be drained. This is determined from field and laboratory tests, or it may be estimated from soil conditions by highly experienced soils engineers. It is the most important and difficult part of the work.
> (b) Average hydraulic gradients in the soil and in the drain.
> (c) Average areas of soil and drain material through which water is flowing (normal to the direction of seepate).

Rough estimates of infiltration rates and drain dimensions and of permeabilities needed to discharge estimated infiltration rates can be made with a Darcy's law nomograph.

2. Use Darcy's law to design the drain, after conventional flow nets have been used for estimating infiltration rates.

3. Use composite flow nets to develop hydraulically balanced solutions for seepage in the soil and in the drain.

Darcy's Law

Darcy's Law may be applied by two different methods after the infiltration rate from the water bearing soil has been obtained by appropriate means. The two methods are:

1. Select a trial cross-sectional area (A) for the filter and compute the required permeability (K) needed to drain the expected inflow (Q) for the given thickness. Darcy's Law would take the following form:

$$K = \frac{Q}{iK}$$

The hydraulic gradient (i), already discussed in Chapter III, would be the largest head (h) that could be developed divided by the length (L) of the drainage path in the drain or h/L. This method, in the writer's opinion, seems rather awkward. It would appear better to determine a thickness based on the K resulting from a filter material gradation which resulted from a grain-size design. The second method of using Darcy's Law takes this approach.

2. Select permeabilities which represent filters constructed from suitable on-site or commercially available materials and determine the required thickness from the following arrangement of Darcy's Law:

$$A = \frac{Q}{Ki}$$

Again the magnitude of inflow (Q) must be available. In the second method the determination of thickness is necessarily for a 1 foot longitudinal strip, thus in reality the value of A is the thickness for a 1 foot wide cross-sectional area. In both methods, care should be exercised to insure that inflow and outflow areas are compatible.

Flow Nets

Flow nets of the composite of the soil and filter zones may be use in the design of filter thickness. A detailed treatment of flow nets is outside the scope of this report and the writer must assume his readers are familiar with flow net concepts. However, several comments seem appropriate. The squares in a flow net are composed of flow lines (in the direction of flow) and equipotential lines perpendicular to the flow lines. When the permeability of a mass changes from a low value (the soil in this case) to a high value (the filter) the "squares" of the flow net are elongated into a rectangle with the flow line dimensio undergoing elongation and the equipontential dimension undergoing compression. This should be expected since less cross-sectional area is required by the higher permeability material to transmit a given quantity of water coming from the lower permeability material. The dimension of the elongated "square" in the direction of flow is termed "c" and the equipotential dimension is "d". Using the expression

$$\frac{c}{d} = \frac{K_f}{K_s}$$

Where K_f is the permeability of the filter and K_s is the permeability of the soil, two procedures are available to determine filter thickness using flow nets (2). The procedures are:

1. Assume filter dimensions and determine their required permeabilitie
2. Start with known (or estimated) permeabilities for the soil and filter and compute the dimensions of the filter.

Again, the second procedure seems the more logical approach. It should also be noted that, for use with flow nets, Darcy's Law may be expresse as:

$$Q = Kh\frac{n_f}{n_d}$$

Where h is the head, n_f is the number of flow lines in the net, and n_d is the number of equipotential drops in the flow net.

<u>Example--Darcy's Law (After Cedergren, 2)</u>

Given an earth dam with a chimney drain [as in Figure 5(a)]. The entire drainage system may be broken into the vertical portion (the chimney) and the horizontal portion (the blanket).

1. Determine rate of discharge using Darcy's Law (regular expression for use with a flow net if a net is made). For this example it is assumed that the inflow into the chimney through the dam is 2 cu ft/day (Q_1) and from the foundation into the blanket is 10 cu ft/day (Q_2). Both quantities are discharge rates per running foot of dam and filter.
2. Assuming the chimney has a cross-sectional area (1 foot wide strip) of 11 sq ft normal to the direction of flow, a head of 300 feet, and a drainage path length (height of chimney) of 310 feet, the required permeability for the chimney is

$$K = \frac{Q}{iA} = \frac{Q_1}{(h/L)(A)} = \frac{2 \text{ cu ft/day}}{(300 \text{ ft}/310 \text{ ft})(11 \text{ sq ft})}$$

$$K = 0.2 \text{ ft/day}$$

3. Any filter material having a permeability of 0.2 ft/day should have an adequate capacity if all the parameters were correctly determined. It would be wise to include some safety factor. Using the permeability approach is justified for the chimney since there is a minimum width (10-12 feet) required so that a chimney may be economically and correctly constructed using normal earth-moving equipment.

The blanket portion of the drainage system will be solved using the second method of Darcy's Law application.

1. Assuming the maximum allowable head (h) in the blanket may not exceed its thickness, the following is used (b denotes blanket dimensions):

$$K_b = \frac{Q}{iA} = \frac{Q_1 + Q_2}{(h_b/L_b)(A_b)}$$

$$Q_1 + Q_2 = Q_b$$

$$h_b = A_b$$

Therefore $K_b = \dfrac{Q_b L_b}{(A_b)^2}$

The length of the blanket is 550 feet, which is equal to L_b.

$$K_b = \frac{(12 \text{ cu ft/day})(550 \text{ ft})}{(A_b)^2}$$

$$A_b = \left(\frac{6600}{K_b}\right)^{1/2}$$

With this expression, any number of trial solutions for thickness (A_b is the thickness of a 1 foot strip) for different permeabilities are possible. Typical solutions for generally encountered materials are:

Washed filter aggregate: A_b = 82 ft

Pea gravel (1/4 inch): A_b = 1.5 ft

Screened gravel (3/8 inch to 3/4 inch): A_b = 0.4 ft

The use of the washed aggregate is not practical or even possible, but either the pea or screened gravel could be used. If the screened grav were used, construction practices would necessarily required a thickne larger than 0.4 feet in most cases.

Cedergren (2) points out that flow through highly permeable material could become turbulent and since the hydraulic gradient does not increase in direct proportion to the seepage velocity or quantity for such flows, error (not necessarily on the safe side) would be introduced in the analysis. He suggested in cases where this could occ that safety factors (10 or more) should be used.

Example--Flow Net Solution

Any example of thickness determination using flow nets will not be presented because of their complexity. Several excellent examples are presented in the Cedergren references (2) (26). Flow nets are a reasonable method of determining the quantity of inflow for filters and could have been used to compute the Q values used in this example.

Darcy's Law Nomograph

Although no example will be presented Cedergren (2) discussed a nomograph based on Darcy's Law which would be of great aid when a large numbers of calculations are required due to numerous alternative design: Solutions are possible with starting values of permeability or thicknes:

Reference to an Alternate Method, Critical Gradient and Filter Thickness

Parcher and Means (4) present an excellent example of filter thickness determination using a flow net and Hazen's formula. The example considers the possible of a quick condition developing in a filter if adequate weight is not present.

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