RECLAMATION

Managing Water in the West

Design Standards No. 13

Embankment Dams

Chapter 5: Protective Filters
Phase 4 (Final)

U.S. Department of Interior
Bureau of Reclamation

November 2011

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Design Standards No. 13

Embankment Dams

DS-13(5)-9: Phase 4 (Final)
November 2011

Chapter 5: Protective Filters

Chapter Signature Sheet
Bureau of Reclamation
Technical Service Center

Design Standard No. 13

Embankment Dams

Chapter 5: Protective Filters

DS-13(5)-9:[1] Phase 4 (Final)
November 2011

Chapter 5 – Protective Filters is an existing chapter within Design Standards No. 13 and was revised to include:

- Addition of historical perspective and mechanics of particle retention
- Addition of zone interface considerations
- Revised gradation selection procedure, especially base soil selection
- Revised pipe perforation criteria
- Addition of laboratory procedures for gradation and material quality
- Addition of construction considerations

[1] DS-13(5)-9 refers to Design Standards No. 13, chapter 5, revision 9.

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Acronyms and Abbreviations

AASHTO	American Association of State Highway Transportation Officials
A&E	architectural/engineering
ASCE	American Society of Civil Engineers
ASDSO	Association of State Dam Safety Officials
ASTM	American Society for Testing and Materials
CEF	Continuing Erosion Filter
CFRD	concrete face rockfill dam
CMP	corrugated metal pipe
Cu	coefficient of uniformity, D_{60}/D_{10}
Cz	coefficient of curvature, $D_{30}^2/D_{60}*D_{10}$
EOS	equivalent opening size
FEMA	Federal Emergency Management Agency
ft^3/min	cubic feet per minute
ft^3/s	cubic feet per second
HDPE	high density polyethylene
HET	Hole Erosion Test
ICOLD	International Commission on Large Dams
lb/ft^3	pounds per cubic feet
mm	millimeter(s)
NEF	No Erosion Filter
OD	outside diameter
NRCS	Natural Resource Conservation Service
PI	plasticity index
PVC	polyvinyl chloride
Q/A	quality assurance
Q/C	quality control
Reclamation	Bureau of Reclamation
SEV	sand equivalent value
TSC	Technical Service Center
USACE	U.S. Army Corps of Engineers
USCOLD	United States Committee on Large Dams
USCS	Unified Soil Classification System
USGS	U.S. Geological Survey
ºF	degrees Fahrenheit
µm	micrometer

Chapter 5

Protective Filters

5.1 Introduction

5.1.1 Purpose

Filters and drains have been recognized as a means of directing and controlling the flow of water through porous media for thousands of years; the earliest documented use of drains is at the Ur of the Chaldees. Filters are used to prevent migration of fines between various zones and foundations of embankment dams. Seepage transport of soil particles between zones can lead to serious consequences and, in extreme cases, failure of an embankment dam. The criteria presented in this chapter are for guidance in the proper design of soil filters, drains, and zoning of embankment dams.

The particular design requirements and site conditions of each embankment dam are unique, and as such, no single publication can cover all of the requirements and conditions that can be encountered during design and construction. Therefore, it is critically important that embankment dam filters be designed by engineers experienced with all aspects of the design and construction of embankment dams.

Embankment dams, regardless of their size, create a hazard potential from the stored energy of the water they impound. Examples, such as Kelley Barnes Dam, which failed suddenly in 1977, show the destructive power of water when it is released suddenly from behind even a small embankment dam. This embankment dam was less than about 40 feet high and about 400 feet long, but when it failed, it released water downstream at an estimated flow rate of over 24,000 cubic feet per second, killing 39 people.

5.1.2 Application of Design Standards

All Reclamation design work, whether performed by the Technical Service Center (TSC), the Regional Director, or an architectural/engineering (A&E) firm, will conform to the design standards.

5.1.3 Deviations and Proposed Revisions

Whenever a design deviates from the standards, the designer should note the deviation and the rationale. The deviation and rationale for the deviation must be approved by the engineers technically responsible for the designs and concurrence obtained from the peer reviewer(s).

Deviations from the Bureau of Reclamation (Reclamation) design standards made by an A&E firm must be approved by the Reclamation Contracting Officer. Any deviation from the design standard must be documented and made part of the design records.

The designer should inform the TSC, via the Web site notification procedure, of any recommended updates or changes for the design standards to meet current design practices.

5.1.4 Nomenclature

Through the decades, a number of terms have been used in association with filter zones and materials. Some, due to the historical precedent, are confusing today. This section will present some of the background for these terms and describe the nomenclature that will be used in this chapter.

It has been a common practice to describe soil based on grain size distribution, or gradation. Since soils behave differently, in an engineering sense, if they are all one particle size or if they have a wide range of sizes, terms came into being to describe these two different classes of soils. As advancements were being made in the development of concrete mix design, it was recognized that aggregate containing roughly equal amounts of sand and gravel made for a stronger and more economical product than an aggregate that was only sand. Therefore, aggregate gradations that had roughly equal parts sand and gravel were called *well graded* because they will do well as a concrete aggregate. In a similar manner, gradations that only included sand sizes were termed *poorly graded* due to the poor performance of that mix design. While broadly (well) graded soils are acceptable in some filter applications, it should not be concluded that they are superior to more uniformly (poorly) graded soils. Uniformly (poorly) graded soils are preferred for use in two-stage designs such as toe drains, and it should not be inferred that they are "poor" or unacceptable for use.

To help alleviate this confusion, new terms were introduced that were more generic to the shape of the gradation curve and did not focus on the performance of a particular gradation. Gradations that included many soil types, and when viewed on the gradation plot had a broad appearance, were named *broadly graded*. On the other hand, a gradation of a single soil type would appear narrow on the gradation chart and was named *narrowly graded*. Since these narrow gradations are also uniform in their distribution, the term *uniformly graded* is also used. Therefore, the following terms are synonymous:

Narrowly graded	=	Uniformly graded	=	Poorly graded
Broadly graded	=	Widely graded	=	Well graded

In the Unified Soil Classification System (USCS), the distinction between well and poorly graded soils is made by use of the coefficient of uniformity, Cu, and the coefficient of curvature, Cz. Well (broadly) graded soils are defined in the USCS as:

$$Cu \geq 4$$

and

$$1 \leq Cz \leq 3$$

Poorly (uniformly) graded soils are defined by:

$$Cu < 4$$

and/or

$$1 > Cz > 3$$

Figure 5.1.4-1 is a gradation plot that illustrates these two groups of soil gradation. This design standard will use the more generic *broadly graded* and *uniformly graded* terminology.

Two other terms used to describe the gradation of a soil are *gap graded* and *skip graded*. These terms essentially mean the same thing and describe the condition when a range of grain sizes are missing from a gradation. The terms came into use upon observation of the gradation test results where some sieves would have little or no soil particles retained. Figure 5.1.4-2 is a gradation plot that illustrates this soil type. This design standard will use the term *gap graded* for these types of soils.

Historically, the terms *filter* and *drain* have held different meanings by different authors, and their use as both nouns and verbs has led to even further confusion. Filter material, when designed using the guidance in this design standard, provides both particle retention and drainage in embankment dams. Therefore, a single material can retain or filter particle movement from a base soil and may also have sufficient permeability to act as a drain. Since the designed material performs both functions, the terms have become interchangeable, especially in relation to where the material is used in the embankment cross section. This has led to some authors using the word *drain* for a *filter* and vice versa. Others have chosen to combine the terms into *filter/drain*, *filter-drain*, and *filter and drain*.

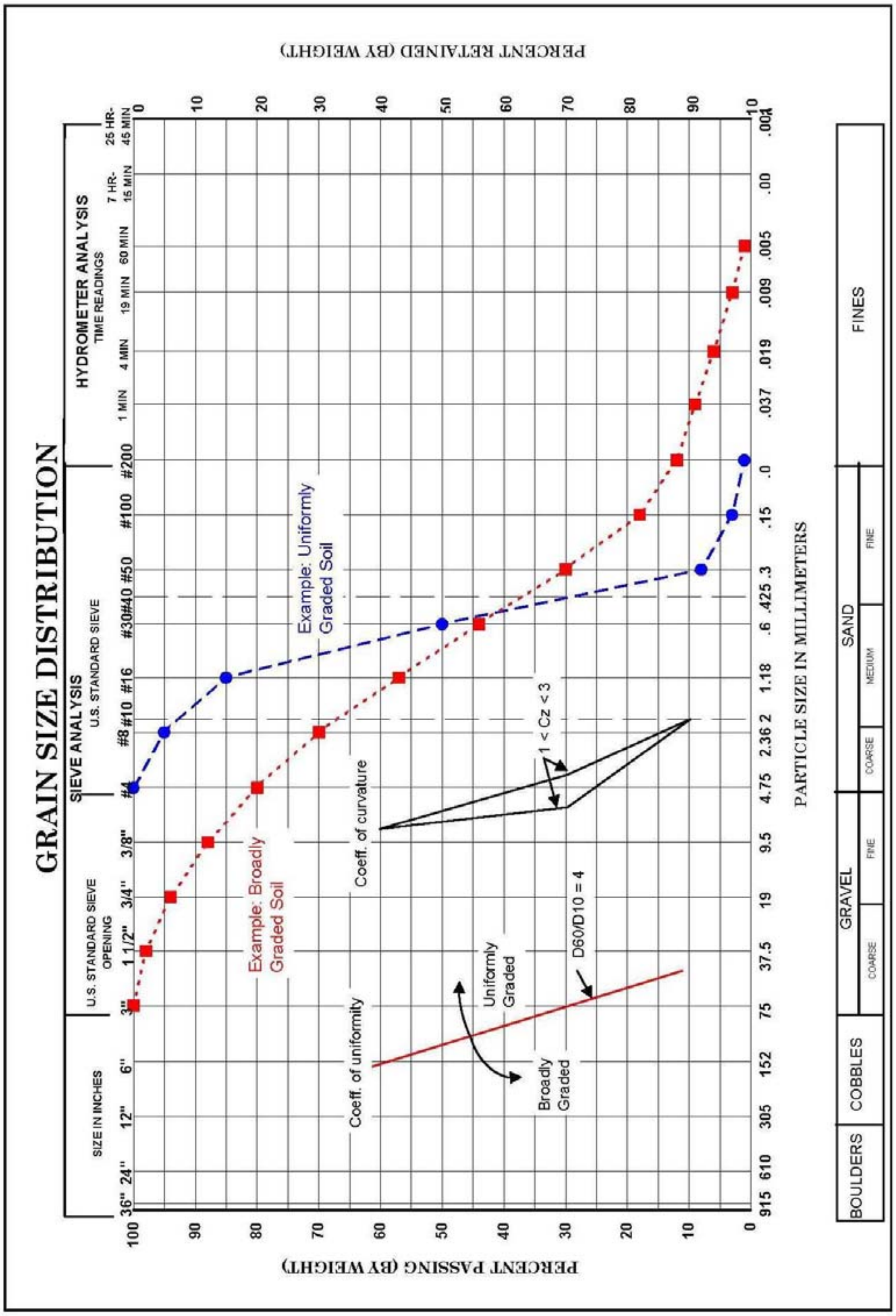

Figure 5.1.4-1. Example of broadly and uniformly graded soils.

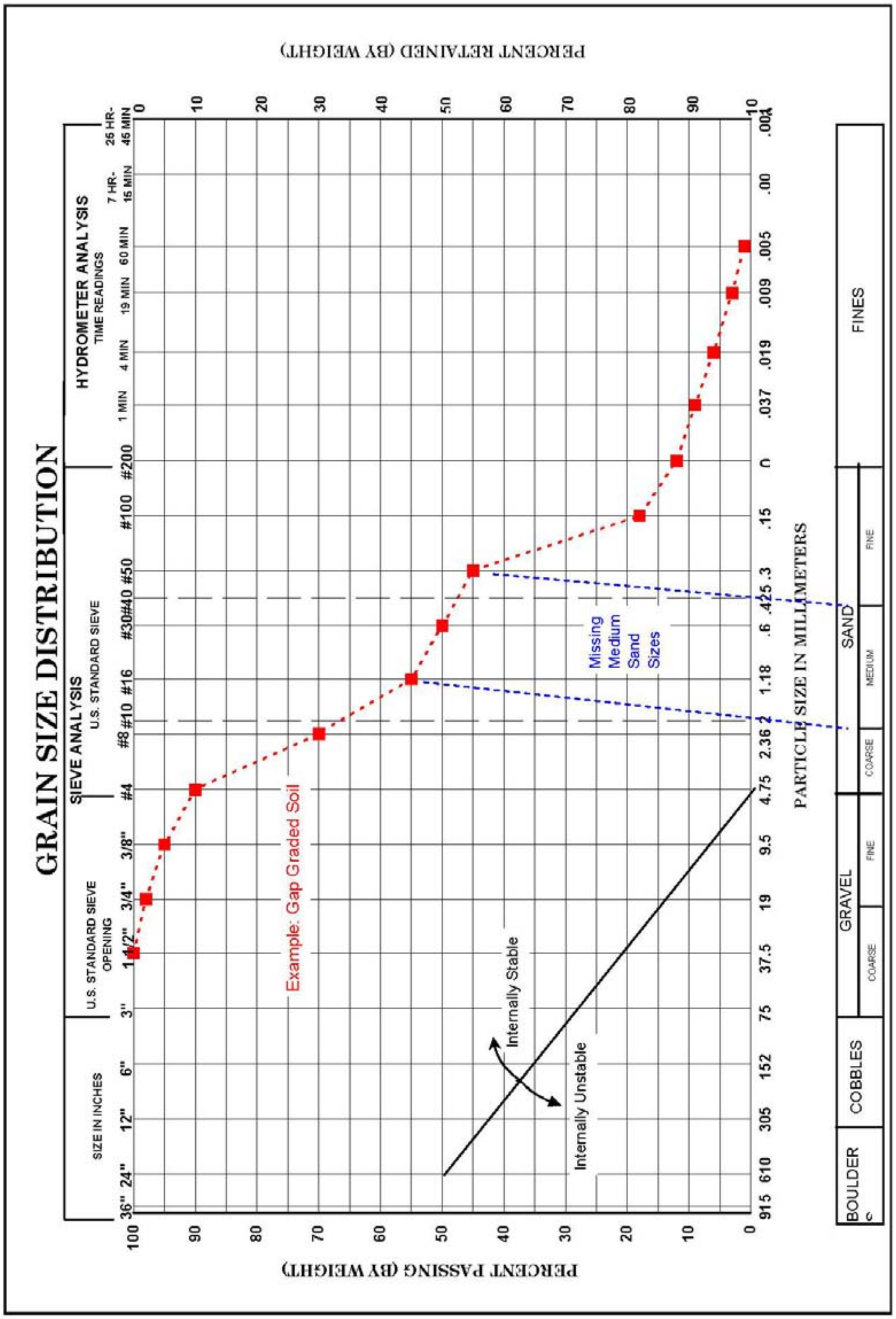

Figure 5.1.4-2. Example of a gap-graded soil.

Typically, the distinction between these terms can be made based on the stage the material satisfies. As described later, a first-stage filter protects the base soil, and its primary function is particle retention. In many instances, a second-stage material will also be used, and its primary function is to provide drainage. While both materials meet particle retention and drainage criteria, the emphasis of the first stage is on particle retention, and the emphasis of the second stage is on drainage. In accordance with this philosophy, this design standard will use the term *filter* in the context of embankment zones as the first-stage material. In a similar manner, the term *drain* will be used for zones that function as second-stage material. As an example, for a two-stage chimney, the first stage would be the chimney filter and the second stage would be the chimney drain. For cases in which both stages are present, the term *filter/drain* will be used.

As far as nomenclature used for algebraic variables, both Terzaghi and Sherard have used lower case "d" to represent the particle size diameter of the base soil and capital "D" for the particle size diameter of the filter material. This nomenclature has been repeated by many authors and is commonly used today. This nomenclature is satisfactory when designing a single filter, but confusion arises when designing two-stage filters since the filter from the first stage becomes the base for the second stage. Therefore, this design standard will use the following nomenclature.

$D_{XX}Y$

Where:

D = Particle diameter
xx = Percent by weight particles finer than particle diameter, D
Y = Material designation where:
- B = Base
- F = Filter (first stage)
- E = Envelope or other drainage element (second stage)

Example:

$D_{15}F$ = The particle size of first-stage filter at 15 percent passing.

5.1.5 Scope

This design standard applies to naturally occurring earth materials or to filters manufactured from such natural earth materials by grading, screening, washing, and crushing. This standard covers design principles and filter criteria including quality, flow into pipes, zone geometries, and construction considerations.

Filters of woven or nonwoven fabrics are generally not recommended for use as protective filters and are excluded from this chapter. They are covered under guidelines for geotextiles in chapter 19 of these standards. A discussion of the shortcomings related to the use of geotextiles is included in appendix B.

Filters are used to prevent movement of soil particles from or between various zones and foundations of embankment dams. Approximately 50 percent of all dam failures are attributed to excess seepage. These failures are progressive in nature and begin with the erosion of a few grains of soil, usually undetected. The loss of those soil grains leads to greater seepage, which leads to more soil erosion. This process continues until it is noticed, but often by this time, it is too late to intervene to hopefully prevent complete failure of the dam.

It is known that many dams crack, are sometimes poorly constructed, may be constructed from highly erodible material, or may have foundation conditions that allow large amounts of underseepage. These conditions are known to produce the potential for severe distress that can lead to eventual failure of dams. Therefore, design elements such as filters are used as a defensive measure to protect these types of structures from the less than desirable conditions that may exist or develop over the life of the structure. This design standard presents the proper design of filters and their use in embankment dams.

The filter design criteria presented here can be applied to the design of a wide variety of granular filters and drains that are included as elements for many hydraulic structures. While the criteria and procedures in this chapter were initially developed for use in embankment dams, they can also be used for drainage elements under spillway slabs, protection of levees against blowout, design of riprap bedding, as well as many other applications.

The design challenge for an embankment dam is to develop a safe cross section that can be constructed from materials available to the site at minimum construction and maintenance costs. Economical design requires the use of materials that protect against failure yet are easily constructed. Since filter materials are some of the most costly materials used in a dam, effort is made to minimize the amount of material used. Therefore, the balance of cost, constructability, and reliability go hand in hand in providing an economically safe structure.

Soil particle movement can occur through two basic mechanisms: backward erosion piping and internal erosion. Backward erosion piping occurs when soil particles are detached at the seepage exit or seepage discharge face of intergranular seepage (water seeping through the pores of the soil). Internal erosion occurs when soil particles are detached by flow in a concentrated leak (such as a crack) from erosion along the sides of the crack or opening. Filters provide protection against these two mechanisms developing into a concentrated (large) leak that could cause excessive loss of water or failure of the structure. A properly designed filter consists of a soil gradation with void (pore) size openings small enough to prevent migration of the base soil. At the same time, a properly designed filter will be sufficiently pervious to offer little resistance to water flow.[2]

Filters serve to accommodate high gradients through a dam by intercepting the seepage flow from the zone containing high gradients (the changes in head over a given distance) and reducing gradients to near zero in the drainage system. The water stopping element of the dam is typically a fine-grained soil that is subjected to a high gradient since the pressure head through the dam must be reduced from the reservoir level on the upstream side to the tailwater elevation on the downstream side. Placing a filter against the fine-grained soil (core zone) prevents the movement of soil particles and protects it against erosion caused by these high gradients.

Additionally, there is a requirement that filter material be of sufficiently high quality so that it will not be able to sustain a crack. In the past, material quality was measured by maximum fines content and plasticity. More recently, it has been found that other types of binders or cementing agents, which were undetected by earlier test procedures, can also result in material that can sustain a crack. See section 5.6.2 for additional discussion on this topic.

5.1.6 Applicability

These filter criteria can be applied to the design of a wide variety of filters and drains that are included as elements specified for any hydraulic structure where excessive uplift pressures may lead to particle migration, boiling, and internal erosion; where seepage flows require control and direction; where the phreatic surface must be controlled below a certain level; where exit gradients must be reduced to an acceptable maximum; where reduction of pore water pressures is required; and where erosion protection is necessary. Interconnected filters become an internal drainage system that functions to protect the structure. The range of hydraulic structures that may require drains includes, but is not restricted to, embankment dams, dikes, levees, slope protection, upstream diaphragms, foundations and abutments, outlet conduits, stilling basins, retaining walls, and canal linings. The filter criteria can be used to design filters in contact with cohesionless soils or cohesive soils, and upon or adjacent to rock. Soil types include all those normally defined by the USCS and Reclamation's Earth Manual [1]. While these criteria were originally developed for new dam design and construction, they can also be used for existing dams. These criteria are also applicable for use in checking filter compatibility (criteria are met) of two zones in an existing structure.

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[2] There are special cases in which water flow (drainage) is not critical, such as in transition zones. Such zones are often in a benign section of the dam.

5.1.7 Acknowledgements

This revision is based on the earlier work of Reclamation authors Thomas McDaniel and Perry Hensley. Some sections of this revision are based on the work produced for the Federal Emergency Management Agency (FEMA) Manual, *Filters for Embankment Dams – Best Practices for Design and Construction* [2]. That manual was a joint effort by Reclamation, the U.S. Army Corps of Engineers (USACE), and the Natural Resource Conservation Service (NRCS). Specific recognition goes to James Talbot (retired NRCS) for the sections on geotextiles and David Hammer (retired, USACE) for contributions on construction practice. Cindy Gray of Reclamation's Client Support and Technical Presentations Office produced most of the figures.

5.1.8 Historical Development

Early researchers determined that a properly designed layer of material covering an area where seepage is discharging could block the movement of the base soil materials while allowing seepage water to continue to be discharged safely. This layer was termed a filter because it was capable of blocking the movement of the base soil particles. Most of the early filter research investigated material designs that were both sufficiently fine to block the movement of the base soil particles and sufficiently permeable to freely pass the seepage water. These studies focused on determining the grain size of a filter required to protect a base soil. The most commonly studied base soils were silty sands because those materials were the most susceptible to backward erosion piping.

The concept of particle retention can be envisioned by considering a container of equally sized spheres. The space between the spheres (voids) will have a fixed maximum opening size based on the diameter of the spheres. The size of a smaller sphere that can pass through these voids can then be calculated. While this is a simple mathematical procedure, since soil particles are not spherical or all of one size, the theoretical application to earth materials is limited. Therefore, development of filter criteria for soils is centered on empirical relationships based on laboratory testing.

5.1.9 Particle Movement and Interfaces

Filters are designed to prevent particle movement from intergranular seepage flow where defects[3] are present in the base soil or seepage water flows only through the pore space of the soil mass. Flow may occur through zones in an embankment or through its foundation. If a soil susceptible to backward erosion is not protected

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[3] Defect as used in this chapter includes cracks, poorly compacted lifts, coarse grained lifts or layers, or other anomalies.

by a filter, the energy of the water moving through the soil may be adequate to dislodge and remove particles at the discharge face. One factor that governs the flow of water through soil is the seepage gradient which is the change in total head between two locations divided the seepage path length (usually where it outlets to the atmosphere or into another zone). Each soil will have a critical gradient based on its properties where, if exceeded at the discharge point, soil particles will be eroded away with the flowing water.

Generally for silts and clays having a plasticity index (PI) greater than about 7, very high gradients (> 100) are required to initiate backward erosion piping[4]. These gradients are usually not achieved in conventional embankment dams and embankment dam foundations.

For cohesionless soils (PI < about 7), and particularly nonplastic soils, much lower gradients will initiate backward erosion piping. The critical gradient in these soils is dependent on uniformity of particle size, mass and size of particles, and density. Soils comprised of particles of fine, uniformly graded sand with no cohesive binder (typically classified as SP or SP-SM) are susceptible to being detached because of low particle mass and lack of interparticle attraction. Larger sand particles or gravels are more resistant to particle detachment because of their greater mass. Broadly graded sands are more resistant to backward erosion piping because the small particles cannot easily migrate through the soil body because they are blocked by larger particles in the mass. Soils that have been compacted or are otherwise naturally dense usually have more resistance to backward erosion piping.

Granular filter material is placed in contact with a surface of the base soil where seepage water will be percolating through the pores of the soil. During construction, compaction is used to ensure a positive contact between the filter and the base soil. This is known as supporting the discharge face. Due to the nature of the granular filter particles and the way these zones are constructed, the sand applies a positive pressure against the soil discharge face. Figure 5.1.9-1 illustrates how the filter in contact with the soil discharge face provides support and prevents soil movement.

As seepage flow patterns develop through embankments, abutments, and foundations, seepage gradients may become large enough to exceed the critical gradient of the soil at the discharge point. When left unfiltered, the unsupported discharge face in which the critical gradient is exceeded is susceptible to particle erosion, forming a cavity or "pipe" that progresses from downstream to upstream. Eventually, a concentrated leak develops in a pipe-shaped cavity, and failure usually follows as the cavity enlarges from erosive forces. This phenomenon is called "piping." Research [3] has shown that a properly graded filter will support the discharge face and preclude the movement of soil particles.

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[4] Except for the case of dispersive soils where a much lower gradient can initiate erosion.

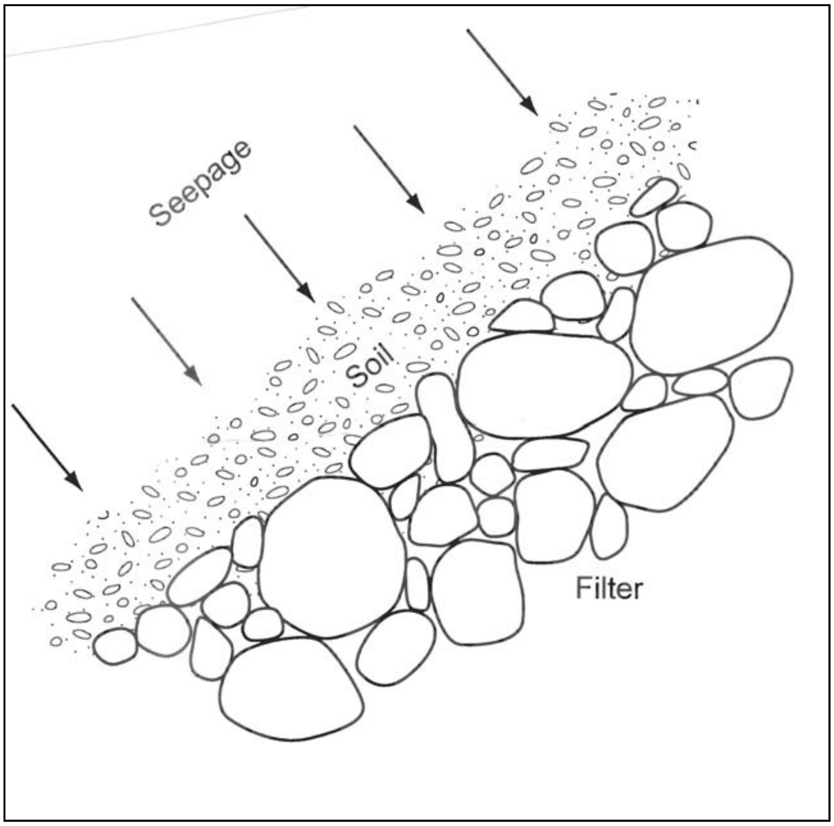

Figure 5.1.9-1. Schematic demonstrating the manner in which a filter prevents the movement of base soils by seepage forces at the discharge face. The filter supports the discharge face with closely spaced contact point as compaction melds the two zones together such that bridging between the contact points prevents any movement of base soil particles into the filter. At the same time, the filter is sufficiently coarse to allow seepage water to escape freely.

Filters are also designed to prevent particle movement from internal erosion along cracks, anomalies, or defects in the embankment. Preferential flow paths can occur in earth embankments, their foundations, or at contacts between the fill and concrete structures or bedrock. In this mechanism of soil erosion, soil particles are detached by slaking along the preferential flow path (i.e., along the walls of a crack in the base soil), and the soil is subsequently eroded by water flowing at relatively high velocity (compared to the velocity of flow in intergranular flow). The eroded particles are then carried through the preferential flow path to the filter face. Most soils are subject to erosion from this mechanism, and modern filter criteria also control this type of erosion. Figures 5.1.9-2, 5.1.9-3, and 5.1.9-4 illustrate the way in which a filter works to prevent internal erosion [3].

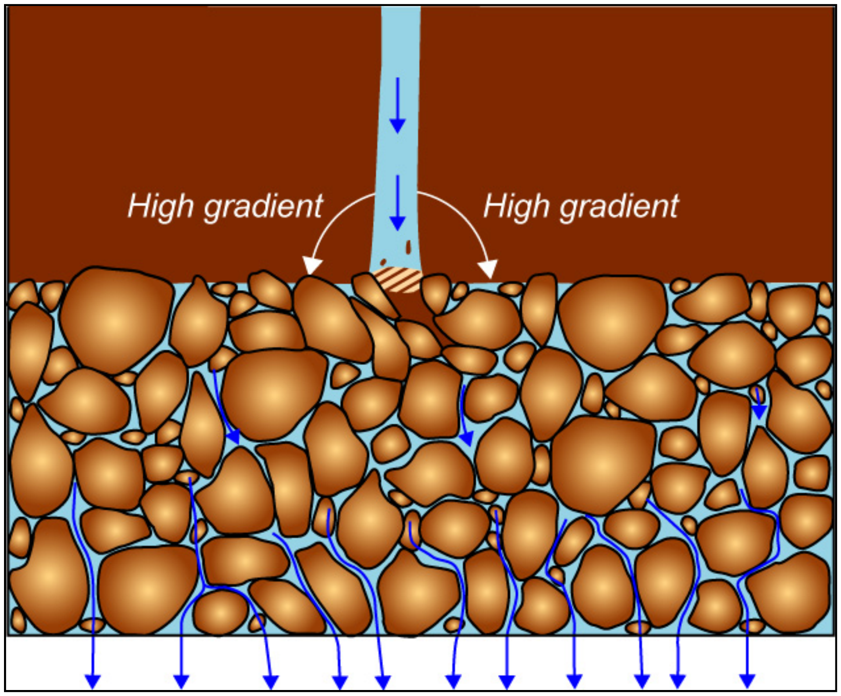

Figure 5.1.9-2. Eroding soil in the crack is caught at the filter face, stopping flow in the crack. High gradients cause hydraulic fracturing from the crack to the adjacent filter.

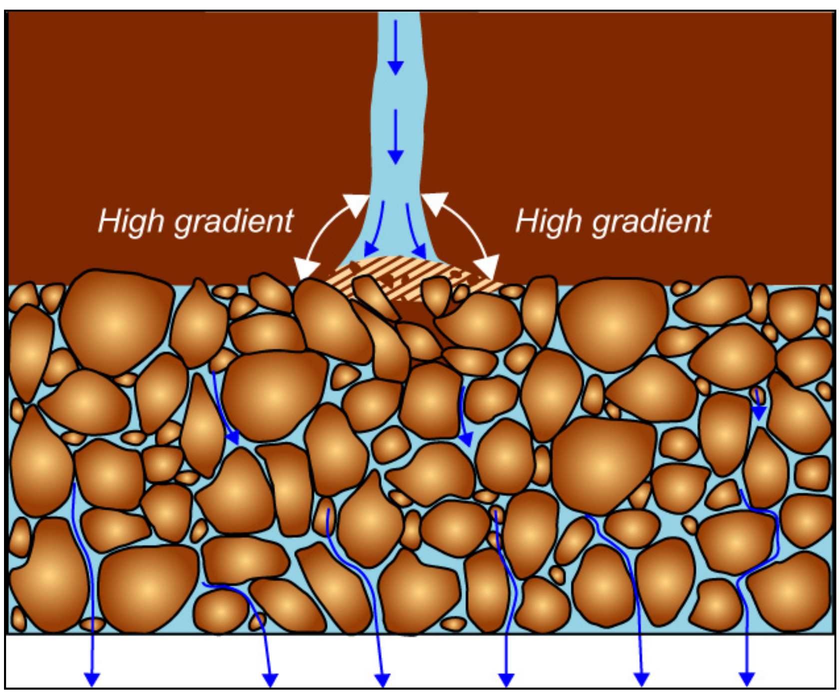

Figure 5.1.9-3. Eroding soil from a crack has been caught at the filter face, and hydraulic fracturing from high gradients between water in the crack and the adjacent filter has caused some widening of the cake on the filter on either side of the crack.

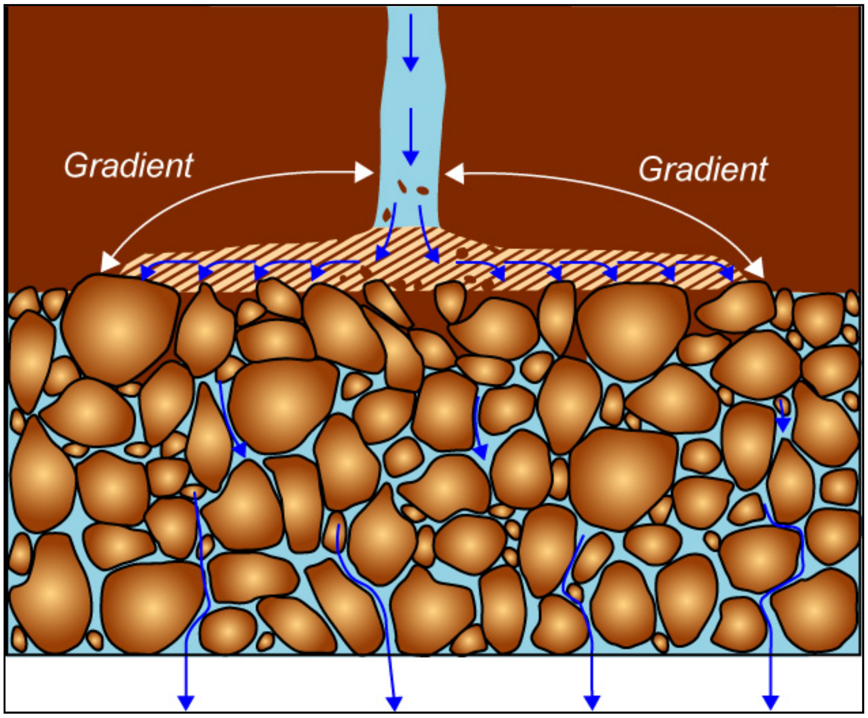

Figure 5.1.9-4. Eroding soil from the crack has been caught at the filter face, and hydraulic fracturing from the high gradients between water in the crack and the adjacent filter has caused further widening of the cake on the filter until the gradient is reduced. The filter cake having a very low permeability covers the width of the crack and some distance on each side of the crack. The remaining filter is open for collecting seepage flow through the pores of the soil between cracks.

5.1.10 Preferential Flow and Internal Erosion

Design for embankment dams requires that cracking or other defects be assumed. Since foundation conditions will not be fully understood until construction and the uncertainty associated with the quality of construction until it is completed, the prudent course of action is to assume that some type of defect will occur in the embankment. Based on historical performance of embankment dams, it is known that cracks or other preferential flow paths are likely at the following locations:

- Upper part of the embankment
- Overly steep abutments or above abrupt changes in the foundation or abutment profile
- At the embankment/abutment contact

- At the embankment/foundation contact
- Around and above a conduit or other structural penetration through the embankment
- At the contact between the embankment and spillway or abutment wall
- Narrow and/or steep cutoff trenches

During construction and during the first few years of service, particularly the first filling of the reservoir, settlement occurs in the dam and foundation.[5] Differential settlement can occur over short distances due to differing settlement characteristics of foundation soils or abutments with variable or steep slopes. These movements in the dam cause stress release. The stress release may be both in the horizontal as well as the vertical direction. Vertical stress release is caused by arching between two or more locations that do not settle as much as a location between them. An outlet works conduit through an embankment is usually a vulnerable location for stress release and cracking. Since the conduit passes all the way through the dam in a transverse direction, it is a particularly critical area for cracking and concentrated leak development. In addition to transverse cracks, longitudinal cracks can also develop due to differential settlement or slope instability. Longitudinal cracking is typically not as serious as transverse cracking due to common seepage paths through dams.

Internal erosion may also initiate in zones of poor compaction or lifts that are coarser than specified. Other zones of poor compaction can occur in exposed surfaces during winter shutdown, diversion gaps, and transverse joints. Openings may result along structures or penetrations through the dam around which the earthfill is poorly compacted. The zone under the haunches of pipes that do not have structural cradles or concrete encasement[6] is a common location for voids and poor compaction. Animal burrows and root holes are also possible causes of openings in embankments.

Some cracks may be very narrow, particularly those caused by hydraulic fracturing. Water penetrating the sides of the crack may initiate some swelling of the unsaturated soil that could close the crack before erosion begins to make it wider. The closing of cracks in this manner has likely saved many dams over the years, but it cannot be depended upon with any certainty because it is a race to see which process progresses faster, swelling or erosion. For dispersive soils, erosion generally wins, which has resulted in the failure of many dams constructed of such materials. For more plastic soils, the reverse is usually true.

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[5] Note that flood control dams may not fill until many years after they are constructed. Since they have not received this critical first filling, they should be considered "new" until that time.

[6] Proper treatment of the haunches is required by this design standard.

Desiccation cracking can occur in the crest of dams constructed of higher plasticity clay in arid environments. These types of cracks can develop over extended periods of time, will usually be worse in extended dry periods, and typically occur in the upper part of the embankment above the normal reservoir water surface. For these reasons, problems can occur during flood events that raise the reservoir to elevations not seen historically. Water can then flow through the desiccation cracks, leading to failure of the dam without floodflows overtopping the dam.

5.1.11 Seepage Collection and Pressure Reduction

Another main function of filter protection in dams and impoundment structures is to provide for the collection of seepage water in such a way as to reduce the seepage pressure in the downstream section of the dam and carry the water to a safe and controlled outlet. In order to do this, the filter and drainage system must have a permeability larger than any of the layers in the dam or foundation that encounters the filter. When the filter zone next to the soil has a permeability lower than some of the base soil strata, pressure will build up in those layers with higher permeability. This potentially unsafe condition may also exist if the filter drainage system does not have sufficient capacity to carry the volume of seepage water. This issue is discussed in more detail later in this chapter, as well as appendix A.

5.2 Applications

The use of protective filters in embankment dams should be the rule rather than the exception. This chapter will address the issues related to the use of filters and the different types of filters used in dams. It is recognized that the cost of filter material, and how that contributes to the overall project cost, is an important issue, especially for smaller dams. For these dams, particularly in remote areas, the cost of filter materials can be a significant portion of the total project cost. In the interest of reducing costs, the designer may feel pressured to reduce or even eliminate the use of filter material. While cost is an important issue, the need to provide a safe structure should not be ignored.

Historically, many small dams (<50 feet high) have been built without any filter or drainage zones, especially those constructed prior to 1980. Additionally, many mid-size dams (50 to 300 feet high) have been built without “modern” filters, although they do contain graded transition zones. Many of the dams in each of these categories have performed successfully for many decades. On the other hand, there have been notable dam failures, including all dam sizes, that have resulted in loss of life and extensive property damage. The failure of dams built without filters led to the general design practice for embankments to change in the 1970s. While mid-size and large dams, which are almost always high-hazard structures, are now constructed with extensive filter elements, some question the level of protection required for small dams, primarily due to the cost issue. It should be noted, however, that since the advent of the dam safety movement in the late 1970s, the failure rate of embankment dams due to internal erosion has remained about the same. The reason for this can be twofold. First, as dams age, they deteriorate due to undetected internal erosion and, over time, eventually fail. Second, smaller structures continue to be built without adequate filter protection and fail upon first filling.

5.2.1 Filter and Drainage Zones

In the past, the decision to use filter protection in embankment dams has been based on whether or not the facility is either low or high hazard. A concern with this philosophy is how the hazard classification can change with time. As rural areas grow and urban areas spread, many low-hazard dams are reclassified as high-hazard dams. The dam owner is then faced with the challenge of upgrading a deficient structure, usually at a significant cost, or breaching the dam and taking it out of service. **Therefore, it is recommended that all new embankment dams, regardless of size or hazard classification, be designed with protective filters.**

Often during safety evaluation of existing dams, questions arise about whether filters should be added. Due to the satisfactory performance of many dams that do not include filters, typically an identified deficiency must be present in these dams to justify the addition of filters. Dams with conduit deficiencies would have a protective filter diaphragm added. Seepage deficiencies through the foundation can be addressed with the addition of a toe drain, and for embankment seepage deficiencies, a chimney should be used. Additionally, for older dams in metropolitan areas with a large downstream population, and associated consequences, filter protection may be added even when no known deficiency has been identified.

The following two sections describe, in general, filter protection as it is used for new and existing dams. A specific description of embankment elements is presented in section 5.2.2.

5.2.1.1 New Dams

Protective filters should be used in all new dams. An additional description of dam layout and the role of filter protection are presented in section 5.2.2. Following are conditions that warrant particular attention to filter design details.

- The core zone of the embankment is nonplastic (PI < 7). Soils are not available to construct a core zone in the dam and a rolled fill cutoff trench with higher PI values.

- The ratio of the depth of water measured from the maximum water surface to the width of the impervious core at the same depth is 2.0 or more. That is, the gradient through the core is greater than 2.0.

- Embankment and/or foundation soils are dispersive clays.

- Foundation soils are erodible and/or susceptible to internal erosion, and an effective cutoff of seepage is not present.

- Differential settlement may cause cracking in a transverse direction to the embankment. Conditions that can lead to differential settlement include steep bedrock profiles, problematic foundation horizons such as soft clays, or collapsible soils. Differential settlement ratios greater than 1.0 foot per 100 feet are excessive.

- Hydraulic fracture of the core zone is possible, based on the potential for arching of zones in the embankment.

- Artesian pressures under or downstream of the dam beneath structures or clay horizons.

- Any penetration through the embankment, including conduits used as either outlet works or spillways.

- Pervious (sand, gravel, and/or cobble foundation layers) foundations.

- Highly jointed or fractured bedrock foundations, including those types of foundations that have been grouted.

- Dams in areas of significant earthquake loading (> 0.25g) that provide sufficient energy that could lead to cracking of the embankment.

- Dams located on active faults.

- Dams on rock foundations where the geologic processes over time have resulted in tensile zones near the rock surface (pull apart).

- Dams on soil foundations subject to liquefaction.

Table 5.2.1.1-1 summarizes conditions and types of filter used to protect against these conditions. Note that the listed conditions are independent of one another and, if multiple conditions are present at a site, then combinations of filter types will be required.

Table 5.2.1.1-1 Conditions encountered in embankment dam zones and how they are protected by filters

Feature	Condition	Possible consequences	Type of filter needed
Embankment	Impervious core composed of nonplastic (PI ≤ 7) materials, excluding dispersive soils (see below)	Particle erosion, cracking	Chimney, blanket, toe drain
Embankment and/or foundation	Composed of dispersive clays	Particle erosion	Chimney, blanket, toe drain
Embankment	Impervious core composed of plastic materials	Cracking	Chimney, blanket, toe drain
Foundation without cutoff	Composed of erodible materials	Particle erosion	Blanket, toe drain
Embankment and/or foundation	Potential for differential settlement of impervious core[1]	Vertical cracking in impervious core	Chimney, blanket, toe drain
Embankment	Hydraulic fracturing of impervious core[2]	Horizontal cracking in impervious core	Chimney, blanket, toe drain
Foundation	Artesian pressure	Particle erosion, blowout of toe	Blanket, toe drain
Embankment	Structural penetration by conduit	Cracking, particle erosion	Conduit diaphragm
Foundation	Pervious materials	Particle erosion	Blanket, toe drain
Foundation	Highly jointed/fractured rock	Particle erosion	Blanket, toe drain
Embankment and/or foundation	Seismic loading and/or locations on active faults	Cracking	Chimney, blanket, toe drain
Foundation	Tensile zones near the bedrock surface	Cracking	Chimney, blanket, toe drain
Embankment	Founded on pervious foundation materials	Particle erosion	Choke (see section 5.2.4)

[1] Conditions that can cause differential settlement include steep and/or irregular abutment profiles and problematic foundation conditions such as discontinuous strata and strata composed of materials of varying thicknesses and composition. Generally, differential settlement ratios of 1 foot per 100 feet are considered problematic.

[2] Usually due to arching of impervious core between adjacent zones that are composed of different moduli (normally stiffer than the core).

5.2.1.2 Existing Dams

There are slight differences of these applications between new construction and modification to existing dams. For new construction, the chimney would be placed near the centerline of the dam for central core designs, whereas the addition of a chimney to an existing dam would require removal of a large portion of the existing embankment to obtain this location. The central location is desirable to minimize hydrostatic pressure in the downstream shell and provide sufficient cover to prevent blow out. However, modifications to existing dams will typically locate the chimney further downstream than what would be used for new construction. When chimneys are located downstream, sufficient overburden must be provided to protect against full reservoir head and blowout. In a similar manner, a blanket added to an existing dam would be shorter because the chimney it connects to is further downstream. Examples of the two arrangements are shown in figures 5.2.1.2-1 and 5.2.1.2-2.

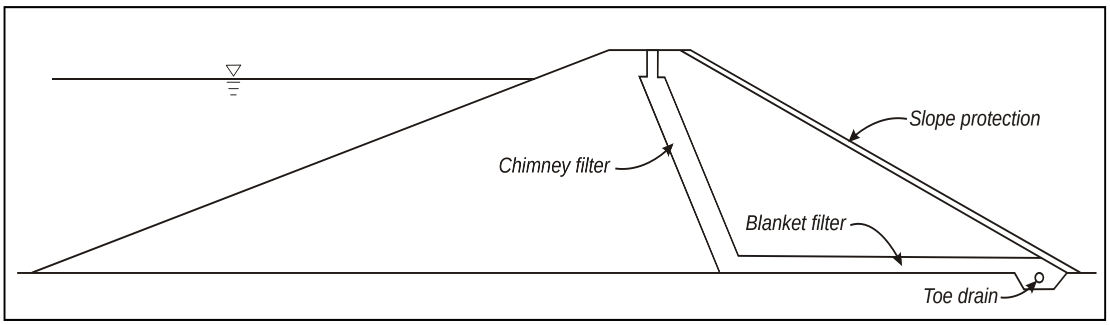

Figure 5.2.1.2-1. Simple cross section showing a chimney used in a new dam.

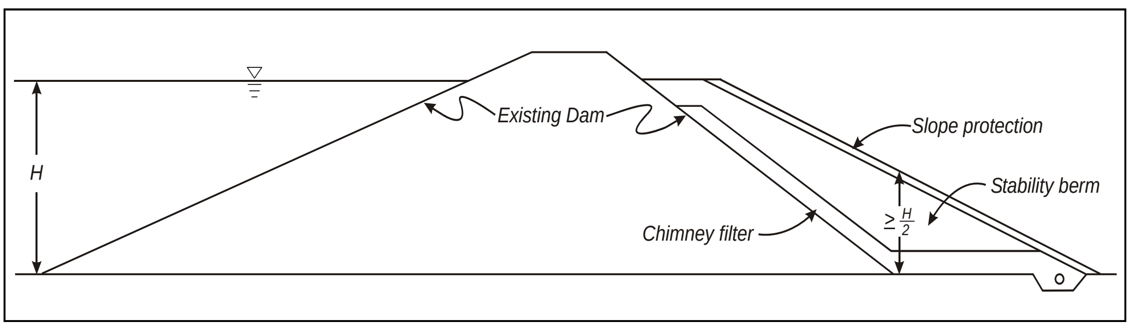

Figure 5.2.1.2-2. Simple cross section showing a chimney added to an existing dam.

5.2.1.3 Lateral and Vertical Extent of Filter and Drainage Zones

While filters used in embankment dams have a theoretical minimum thickness, this dimension is not used in design because construction considerations will generally control minimum thickness. Filters can be difficult to construct, and thin or nonexistent coverage will leave "windows" in the protection, rendering the filter useless. An example of this problem is presented in Attachment D, Example – Inadequate Filter and Drain Geometry. For this reason, construction considerations are typically the deciding factors in specifying filter thickness. The special case of seismic offset may supersede filter width based on construction considerations. In seismically active areas, it may be possible that the dam will experience differential offsets of several feet. In cases where an embankment crosses an active fault, offset can be even more severe. The estimation of the magnitude of either type of offset is beyond the scope of this chapter, but a conservative factor of safety for filter width should be used. Filter widths more than two times the maximum expected offset are recommended.

Once the minimum thickness based on construction considerations has been met, the thickness or width can be determined if the quantity of flow resulting from seepage or cracking is known. For major designs, this flow quantity can be computed by methods presented in Reclamation Design Standard No. 13, Chapter 8 - Seepage [4] or methods presented by Cedergren [5]. The width should be conservative so that a factor of safety is provided against unknown geotechnical conditions, inaccuracies in design parameters, deficient construction practice, etc.

In most cases, the vertical extent of filter protection in a dam (chimney) should be to the crest of the dam. Some designers may prefer to end the chimney at the elevation of the maximum normal pool elevation, also known as the top of active conservation (TAC). This practice is also appealing due to difficulties in constructing a chimney in the narrowest portion of the embankment. The argument against this practice is that the most likely location of cracks in a dam is at the crest, so chimneys should be taken to that elevation. In cases where freeboard exists above the maximum flood pool elevation, to provide protection against wave runup during maximum flood events, the chimney can be terminated at the maximum flood pool elevation.

The lateral extent of filter protection on abutments (blanket) is dependent on canyon or valley geometry and geologic conditions. For broad or wide valleys (gentle abutment slopes as found in earth foundations), the blanket should be extended up to the elevation of maximum normal pool (TAC). For cases where abutment slopes are steep, such as in canyons, the condition of the rock will dictate the extent of protection. For good quality rock with little fracturing, no protection is needed. For highly fractured rock where seepage conditions are expected to be large, blanketing is required. Note that in this situation, blanketing should be used regardless of the amount of foundation grouting or surface treatment.

Where chimneys intersect steep abutments or structures (concrete gravity sections, spillway walls, etc.), the chimney should be flared in order to increase its surface area on the abutment or section as described in section 5.2.2.4.

5.2.2 Protective Filters for Embankments

Embankment dam seepage may be controlled by the use of seepage barriers and filter/drainage zones. Seepage barriers are intended to prevent or decrease seepage, while filter and drainage zones are intended to safely control seepage.

The most commonly used categories of filter and drainage zones used in design of embankments are described in this section. Some designs will include only one component or category of filter and drainage zone, but most designs will include several.

Figure 5.2.2-1 is a composite diagram showing most of the major categories of seepage control zones normally found in central core embankment designs. Rarely would all of these zones be included in any one design. The purpose of figure 5.2.2-1 is to provide a diagrammatic description of the various zones.

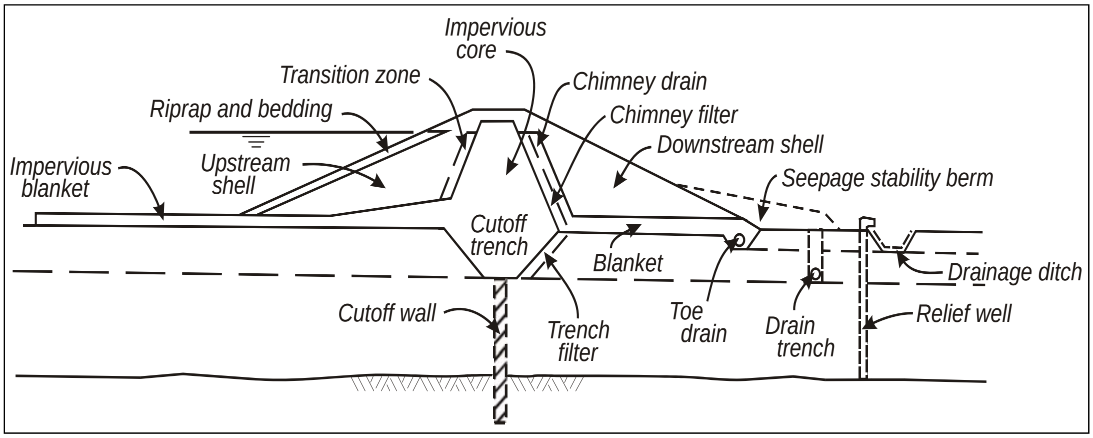

Figure 5.2.2-1. Typical embankment dam design elements found in a central core design.

Components of a modern embankment dam illustrated in figure 5.2.2-1 are:

Impervious Core – Zone of low permeability soil that acts as the water barrier in the dam.

Cutoff Trench – A cutoff trench to rock or other low permeability strata that is integrated with the overlying core.

Upstream Shell – Zone of higher strength soil to support the upstream face of the core. The geometry of the upstream core is sometimes dependent on the rapid drawdown loading case.

Transition Zone – A zone on the interior side of the upstream or downstream shells. Upstream transition zones can also function as crack stoppers.

Chimney Drain – Zone that carries away seepage coming through the chimney filter and delivers it to the blanket drain. It also acts as a transition zone between the chimney filter and the downstream shell. Usually, this zone is composed of gravel-size particles.

Chimney Filter – Zone that protects the core from internal erosion and cracking. Usually, this zone is composed of sand-size particles.

Riprap and Bedding – Riprap is the rock layer that protects the upstream slope of the dam against erosion caused by reservoir wave action. Bedding under riprap protects against particle movement of the protected zone after reservoir drawdown.

Downstream Shell – Zone that supports or buttresses the chimney and downstream slope of the core.

Blanket – Zone that provides foundation hydrostatic pressure relief for pervious foundations and protects against particle movement in soil foundations. It also provides an outlet for seepage water collected by the chimney and from the foundation.

Toe Drain – Collects water from the blanket drain, as well as any foundation seepage, and safely conveys it away from the embankment.

Trench Filter – Zone on the downstream face of a cutoff trench that provides foundation hydrostatic pressure relief for pervious foundations and protects against particle movement in soil foundations.

Drain Trench – Collects water from foundation seepage, and safely conveys it away from the embankment.

Drainage Ditch – Open trench downstream of the dam that collects seepage water. It is most effective when it extends into a pervious layer. It may also be used to collect water from relief wells.

Relief Well – Collects seepage water in the foundation that cannot be collected by toe drains due to overlying impervious layers. It is typically used to reduce artesian foundation pressures in confined layers.

Impervious Blanket – Extends the seepage path and increases the head loss zone for dams on pervious foundations when a cutoff under the dam is not practical. Upstream blankets are integrated into the core of the dam.

Cutoff Wall – Vertical water barrier. Cutoff walls are used as the cutoff through soil foundations or pervious rock such as highly fractured rock. Cutoff walls are usually deep trenches backfilled with cement-bentonite, soil-bentonite, concrete, etc.

Another type of zone often used in modern dam designs is a filter diaphragm around a conduit extending through an embankment. This category of zone is described later in this section.

Elements that are needed in a particular embankment design depend on geology, site conditions, available materials for construction, loading conditions, and economics. Detailed embankment design is beyond the scope of this chapter.

Many embankment designs for seepage control include both foundation and embankment filter/drainage zones that work together to provide a complete system. In addition to filter and drainage zones, most designs employ various methods to intercept seepage and reduce the quantity of flow and hydraulic gradient.

5.2.2.1 Central Core

For central core dams, the primary water barrier (also called the core) will have low permeability but, as is typical for such materials, will have relatively low strength. Availability of suitable core material may be limited depending on the site. For these reasons, it may be desirable to limit the size of the zone. If abundant material is available, the entire dam can be made out of this single zone, which is known as a homogenous dam, but this is not recommended. When the size of the core is minimized, the side slopes are steep and require support. Support is provided by upstream and downstream shells. Since the purpose of the shell is to support the core, it only has to provide strength for that purpose. This central core and shell arrangement is illustrated in figure 5.2.2-1.

As far as seepage through a central core dam, it is generally desirable to obtain full head loss near or just downstream of the dam centerline. Depending on the material used to construct the core, this may be achievable by the core itself. If not, and also to ensure that the head loss is achieved, drainage zones are provided on the downstream face of the core, also known as a chimney. The zone immediately against the core is termed the chimney filter and provides drainage and particle retention as described previously. If needed to provide adequate capacity, a second zone downstream of the chimney filter is included, known as a chimney drain. These two zones ensure that no excess head will be present downstream of their locations. These zones are included in the cross section between the core and downstream shell as shown in figure 5.2.2-1.

5.2.2.2 Diaphragm Core

Today, diaphragm dam designs are typically concrete face rockfill dams (CFRD) and, more rarely, asphaltic concrete faced. As the name implies, the diaphragm is a concrete or asphaltic concrete slab on the upstream face of the dam. While the concrete acts as the water barrier, a secondary “semi-impervious” soil material is used under the slab to attenuate any seepage that may come through the slab joints. Beneath this impervious layer are first and second stage filters that also act as a transition zone to the rockfill section that constitutes the body of the dam.

In the past, some dams have been constructed with the core located in the upstream one-third of the cross section, and in some cases, the core is quite thin, approaching a true diaphragm appearance. This layout is not frequently utilized due to concerns about upstream slope stability and the high gradients imposed on thin sections. If such a section is used, it must be protected by filters in a manner similar to that used for CFRD.

5.2.2.3 Chimneys

Chimney filters are used to protect an impervious core from potential internal erosion failures and, at the same time, effectively control the phreatic surface through the embankment. A typical chimney under construction is shown in photo 5.2.2.3-1. The use of a chimney drain is dependent on the expected amount of seepage through the core; cracking potential, especially related to seismic loading; and composition of the downstream shell. If the downstream shell is not filter compatible with the filter (as defined by the filter criteria in this design standard), a transition zone or chimney drain will be required. In many situations in the Western U. S., rockfill is used for shell material due to its high strength and low cost. In this situation, an additional zone or zones may be required between the chimney drain and the shell. Since the drainage function has been met by the chimney drain, these zones are usually called transition zones. Particle retention criteria should be met between these transition zone(s) and the shell.

Photo 5.2.2.3-1. Two-stage chimney being constructed in zoned dam by concurrent method of construction.

Vertical and inclined geometries are commonly used for design of filter and chimney drains in an embankment dam. Note that while a vertical geometry is similar in appearance to a traditional house chimney, inclined geometries are also called chimneys. The type of geometry used is a function of the dam size, construction method, and core geometry as described in the next sections. Section 5.8 includes discussion of construction considerations for these two geometries.

Vertical chimneys are used most often where impervious core material is scarce and the downstream slope of the core is vertical. Additionally, vertical chimneys are sometimes used where the dam is a homogenous impervious structure where the chimney is constructed by the trenching method as described in section 5.8. The primary advantage of a vertical chimney is that maintaining proper location during construction is more straightforward and dependable than when constructing an inclined chimney. This results in being able to specify a smaller width (say 4 or 5 feet), which requires less material.

5.2.2.3.1 Inclined Chimney Filter/Drainage Zones

Inclined chimneys can be constructed in one of two ways along with the adjacent core material and downstream shell. The first, and preferred method, is to construct one lift ahead of the adjacent zones, and the second method is one lift behind as described in section 5.8.

5.2.2.3.2 Vertical Chimney Filter/Drainage Zones

Vertical chimneys are sometimes constructed through core material by placing several lifts of that zone and then trenching back through those lifts. The trench is then backfilled with filter material and compacted. This method is also sometimes referred to as the trench back method. This process is repeated until the full height of the chimney is achieved. (See section 5.8 for additional explanation of this construction procedure.) Note that the trenching will require that the top of the chimney from the previous trench be exposed by the current trench.

5.2.2.3.3 Chimney Width

In addition to construction considerations, four factors influence the width of vertical or inclined filters:

1. Orientation of the filter; vertical or inclined

2. Loading condition; static or seismic

3. Dam height; large (> 40 feet) or small (< 40 feet)

4. Hazard classification; high or low

For use in this design standard, filter width is defined as the horizontal measurement across the filter. The filter thickness is defined as the measurement normal to the slope. For the special case of vertical filters, the thickness equals the width.[7] When filters are placed against a slope, the width is always greater than the thickness. The difference between width and thickness increases as the slope becomes flatter. Narrow widths on flat slopes can lead to small thickness, which can be problematic due to the "Christmas tree" effect described later.

When a filter is being designed to address seismic issues, the size of the filter is controlled by the maximum deformation expected from the seismic event. Deformations come from foundation fault displacement, slope failure, foundation or embankment liquefaction in existing dams, and nonliquefaction settlement of the embankment or foundation. Generally, filter size should be at least twice as large as the expected deformation (horizontal or vertical). This criterion applies regardless of the size of the dam.

When seismic protection is not required, filter width is typically controlled by proven construction methods. Proven methods indicate that inclined chimneys can be reliably constructed at 6-foot and wider widths [7], and vertical filters can be reliably constructed at 4-foot and wider widths. For ease of construction of inclined filters in large dams, 8- to 10-foot widths are commonly used so that over-the-road trucks and smaller dozers can be used; however, contractors prefer widths up to 16 feet horizontally when bottom dump loaders (scrapers) are used to place the material. Economic considerations sometimes dictate the use of zone widths as narrow as 3 feet, which is about the practical minimum width for a chimney. Narrow zones require special placement procedures and very close inspection during construction. The crack resisting/self-healing capabilities of narrow zones are also less than wider zones, and they should not be used if adequate materials are economically available. Often, reduced placement costs of wider zones will offset increased materials cost where narrow zones are contemplated. Cost considerations should only be the deciding factor when narrow zones meet the design requirements (hydraulic capacity, crack stopping, filtering, accommodation of postulated seismic movement, and self-healing) adequately.

Vertical filters are typically placed using some type of moveable form or spreader box.[8] The arrangements vary, and some are proprietary technology. Vertical filters can also be constructed using the "trench back method." In the trench back method, several lifts of adjacent earthfill are placed, and then a trench is excavated through this fill. The trench is typically 2 to 3 feet wide and not deeper than 3 feet (for worker safety). The trench is then backfilled with horizontal lifts. The trenching and backfilling procedure is repeated until the entire height of the chimney is completed. It should be noted that contamination may be more likely with this method, and the method results in vertical contacts. When constructing zones of differing moduli (stiffness), differential settlement can occur, which can lead to arching across the chimney.

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[7] For additional discussion, see section 5.8.1.
[8] For additional discussion, see section 5.8.2.

When narrow inclined zones are used, the designer should realize that placement procedures do not result in straight interfaces between filter drains and surrounding zones and many have more of a “Christmas tree” appearance as shown in figure 5.8.1-3. The specified minimum width should account for the “Christmas tree” configuration to ensure adequate drainage capacity. Also, the specifications should prohibit the use of construction equipment and placement methods that allow serious segregation[9] to occur.

5.2.2.4 Appurtenant Structures

In the following sections, the use of protective filters around or adjacent to appurtenant structures including conduits, concrete dam sections, spillway chutes, and outlet works stilling basins is discussed. Protecting the interface between the embankment core material and these concrete structures is critical because this interface is a preferential location for a crack to form.

5.2.2.4.1. Conduit Filter Diaphragm

Protection of conduits and other penetrations through embankment dams cannot be overstated. These conduits will establish a preferred seepage path directly through the embankment from the reservoir to the downstream toe. This condition was recognized in the past, and the remedy at the time was to include antiseepage collars around the conduit, the idea being that the flow path at the embankment conduit interface would be lengthened. It is now known that the inclusion of these collars prevented compaction equipment from getting next to the conduit, and adequate compaction was often not achieved. Even with special compaction this can result in a low-density zone surrounding the conduit to the outside limits of the collars. A preferential seepage path can exist at the outside limits of the collars. An additional problem results from differential settlement and cracking between the two density zones. The potential outcome of this condition is shown in photo 5.2.2.4.1-1. While the use of seepage collars has not been permitted by Reclamation since the 1980s, their use by others, especially on small dams, continues today. The proper method of protecting a dam against internal erosion failure along conduits is through the use of filter diaphragms.

A conduit filter diaphragm is that portion of a chimney filter that encases the structure. In the case when a conduit is being repaired or replaced in an existing dam, the diaphragm will have limited horizontal and vertical extent. Filter diaphragms are used in situations in which filter protection needs to be added to existing structures, as described in section 5.2.5. It should be noted that when a chimney is used in an embankment cross section, it will surround any conduits, and a specific filter diaphragm is not needed. The filter diaphragm surrounds a conduit passing through the embankment, and its purpose is to intercept intergranular seepage along the embankment/conduit interface and prevent

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[9] For additional discussion, see section 5.8.3.

internal erosion of those soils, as well as intercept cracks in the surrounding earthfill that could be caused by differential settlement of the embankment caused by the presence of the conduit.

Photo 5.2.2.4.1-1. Embankment dam breached after piping along the conduit. The view is upstream. Note precast concrete pipe placed on a concrete cradle that did not completely fill the haunch and the use of seepage collars. Note that the cradle only partially fills the haunch.

5.2.2.4.2 Filter Considerations Near Concrete Sections

Special attention must be given to the junction of embankments with concrete structures such as concrete dam sections, spillway walls, lock walls, and powerhouses to avoid internal erosion along the slabs or walls. Settlement of an embankment abutting a high concrete wall can create a tension zone in the top of the embankment similar to that occurring next to steep abutments. Battered concrete contact surfaces will ensure that the fill will be compressed against the wall as consolidation takes place. The interface of an earth embankment and a concrete structure should be aligned at such an angle that the water load will force the embankment against the structure to reduce seepage along this interface. An embankment wraparound to transition from a concrete dam to an adjacent earth embankment is recommended, as shown in figure 5.2.2.4.2-1. A filter and/or drain provided downstream of the embankment core and beneath the downstream portion of the embankment should be carried around to the downstream contact with the concrete structure.

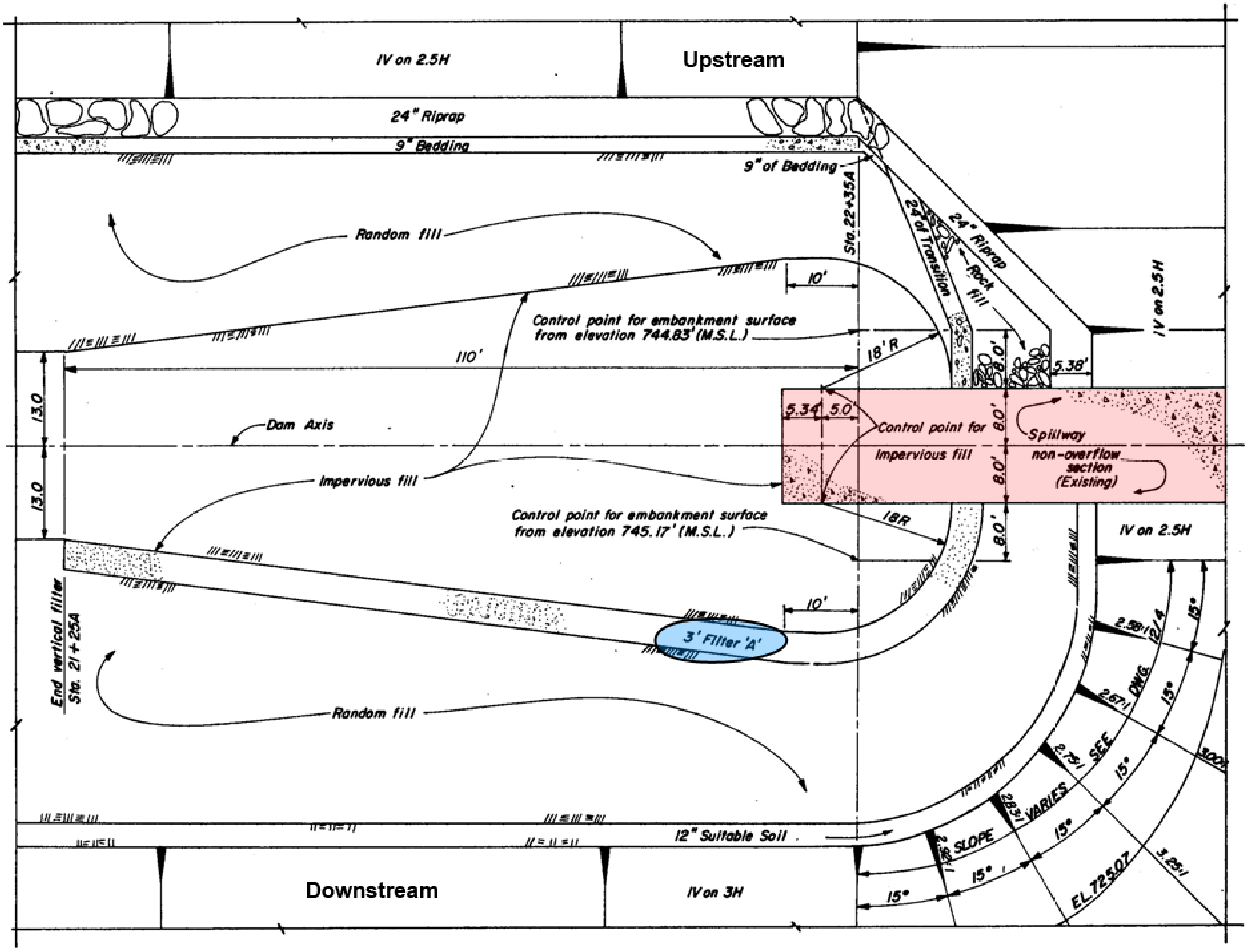

Figure 5.2.2.4.2-1. Filter protection used in the embankment section as it abuts the concrete section of a composite dam.

5.2.2.4.3 Other Structures

Filter and drainage zones are frequently placed around appurtenances to provide protection along the structure. Such structures include spillway chutes and outlet works stilling basins. Photo 5.2.2.4.3-1 shows a drainage zone being constructed next to a battered concrete wall that is part of a spillway chute. In this application, perforated pipes in a gravel backfill are used to provide drainage behind the wall. Since the gravel drain is not filter compatible with the foundation, an intervening sand layer is used to provide filter protection. This is a two-stage system used to protect the foundation while providing drainage for the wall.

Photo 5.2.2.4.3-1. Filter and drainage zones to provide pressure relief and drainage of backfill next to training wall for a spillway chute. (Photo courtesy of NRCS, Texas.)

5.2.3 Protective Filters for Foundations

The major types of foundation filters and drains are described in following sections. The interrelationship between these foundation elements and embankment filter zones is also addressed.

5.2.3.1 Blankets

Blankets may be included in embankment designs both to collect seepage from foundation horizons and to provide an outlet for seepage collected by a chimney filter/drainage zone. Since a blanket is at the interface between the embankment and foundation, it could be classified as either an embankment or foundation element, but for this standard, it is grouped with foundation.

Blankets must provide filter compatibility between foundation soils or bedrock that is not filter compatible with the overlying embankment. A properly designed blanket will protect finer embankment soils from internal erosion into underlying coarser foundation soils or bedrock with joints and fractures as shown in photo 5.2.3.1-1. It can also protect foundation soils from internal erosion into a coarser overlying embankment zone.

Photo 5.2.3.1-1. Pressure washing joints and fractures in bedrock prior to dental grouting and covering with a blanket under the downstream shell of a dam. (Photo courtesy of NRCS.)

Situations in which blankets are required:

- When a chimney is included and there is no clear path for discharge, such as a sand and/or gravel layer, a blanket drain must be included.

- When the downstream shell is founded on soil deposits and the downstream shell soils are not filter compatible with the foundation soils, a blanket is required.

- Blankets are intended to collect foundation seepage and transmit any seepage collected by a chimney to the downstream toe drain. Blankets are not intended to control the phreatic surface through the dam since the core material will have a higher horizontal permeability than vertical permeability due to the material being placed and compacted in horizontal lifts. Interception of primarily horizontal seepage is achieved by a vertical drainage element such as a chimney.

- When the downstream shell is founded on a pervious sand and/or gravel foundation and the downstream shell soils are filter compatible with the foundation soils, a blanket is not required. This is because the foundation soils effectively act as a blanket zone. This configuration is independent of whether or not a chimney is used.

An example of a two-stage filter/drain blanket is shown in photos 5.2.3.1-2 to 5.2.3.1-4. In this application, shown adjacent to an outlet works conduit, the first stage filter is placed on the foundation to protect against soil erosion caused by seepage flow from the foundation into the downstream shell. Over that layer, the second stage gravel layer is placed that provides drainage of the collected water to the downstream toe of the dam. Over that, another first stage filter is placed, which prevents erosion of the overlying shell into the blanket drain. This blanket then serves the purpose of protecting two seepage paths: one from the foundation and the other from the shell. Note that seepage through the shell can come from a phreatic surface that is not adequately attenuated by the chimney or by precipitation that can percolate through the shell.

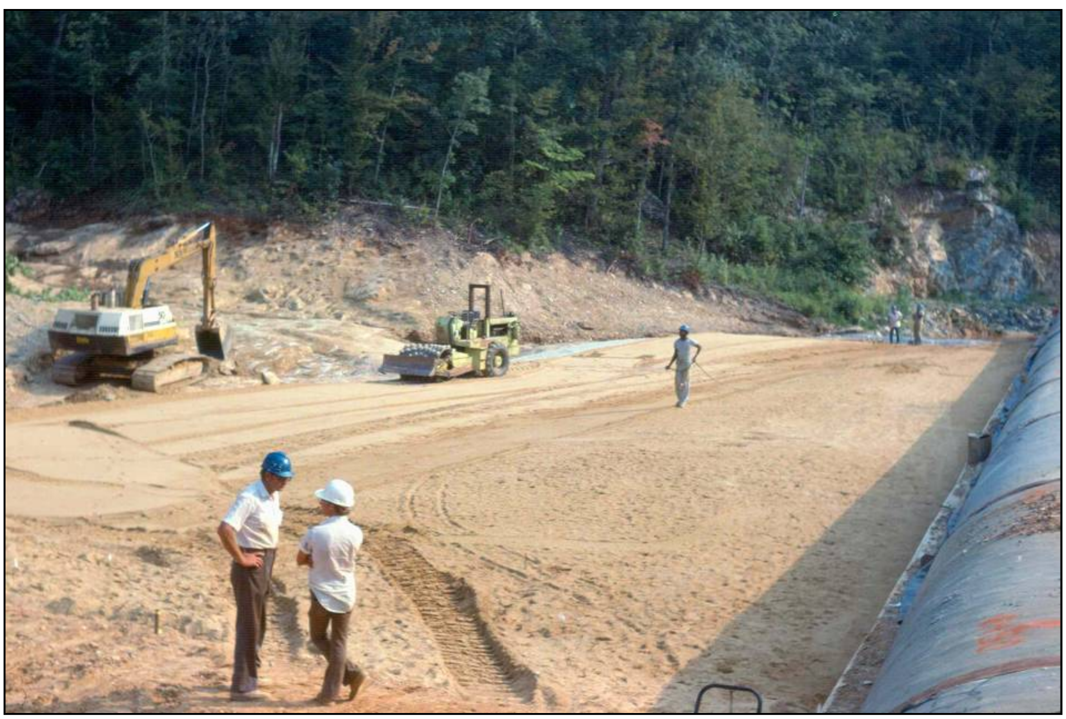

Photo 5.2.3.1-2. Filter being placed on the bedrock surface under the downstream shell of an embankment. View is toward downstream toe. Conduit is to the right of the photograph. Exposed bedrock not yet covered is in the background behind trackhoe. (Photo courtesy of NRCS, Alabama.)

Photo 5.2.3.1-3. Gravel blanket being placed over filter shown in photo 5.2.3.1-2. (Photo courtesy of NRCS, Alabama.)

Photo 5.2.3.1-4. Filter placed over gravel blanket shown in photo 5.2.3.1-3. (Photo courtesy of NRCS, Alabama.)

Assuming that capacity requirements have been met, the minimum practical thickness per stage is about 18 inches with a total desired thickness of not less than

36 inches. On steeper terrain or slopes, this may require special equipment and placement techniques, as well as more intense inspection than normal. When considering these concerns, the more prudent choice is often a thicker blanket. This reasoning also applies to filter/drains and transitions on the slopes of impervious cutoff zones, toe drain trenches, etc.

Designing filter and drainage elements for coarse foundations can be problematic due to the many unknowns that exist even after extensive site characterization studies. Photo 5.2.3.1-5 shows a foundation of a dam built in 1920. While seepage performance and geologic exploration indicated a pervious foundation, the amount of open work observed after excavation remained surprising. This problem is especially difficult for new dams because initial reservoir filling will be the first loading condition. Experience has shown that it is easy to underestimate seepage that flows through these types of foundations. Techniques for estimating these flows have changed over time, mostly due to computational advancements. Whether the estimate is made by hand calculation or by computer, the material property assumptions will dictate whether or not an a reasonably accurate prediction is made [8].

Photo 5.2.3.1-5.—Open work present in the right abutment foundation of Ochoco Dam. The abutment consists of landslide debris.

Parametric studies should be performed assuming a range of permeability and anisotropy for the critical foundation materials [9]. Since the best understanding of foundation conditions is not available until after excavation, the design should be based on the worst reasonable foundation conditions that can be expected. The design should be modified if excavation reveals unforeseen conditions.

5.2.3.2 Toe Drains

Drainage trenches at the downstream toe of embankment dams, also known as toe drains, have been used in embankment dam design for decades. As with other types of filters and drains, the design and layout of toe drains have changed through time. These types of drains are most often constructed near the downstream toe of the embankment, although, in some applications, they are placed under the downstream shell, a practice that should generally be avoided because removal of the shell would be required if repairs are needed. The purpose of a toe drain is to collect seepage from two sources: the chimney/blanket drains and foundation seepage below the dam (underseepage). Toe drains placed on dam abutments will also collect abutment seepage. In any of these instances, the intercepted flow should result in a reduction of hydrostatic pressure under the dam and downstream of the toe.

Toe drains should consist of a perforated pipe surrounded by a gravel drain which, itself, is surrounded by a sand filter. This arrangement is known as a two-stage toe drain. An example of a two-stage toe drain is presented in figure 5.2.3.2-1. While foundation conditions vary, this arrangement is considered the minimum necessary for an effective drain. In the case of pervious foundations, the importance of collecting seepage and, more importantly, reducing hydrostatic pressure cannot be overemphasized. For pervious foundations, it will be tempting to cut costs, and since drains are high-cost items, they may be the focus of such efforts. As described in Section 5.4.1.6, "Filter Barriers," such an approach can lead to a design that does not achieve the goal of pressure reduction and, in the case of modification to existing dams, can make the existing situation worse. Single stage toe drains (a drain consisting of only filter sand and a drain pipe) may also be considered in the interest of minimizing costs. Again, single stage toe drains are not recommended due to uncertainties in foundation conditions and structure performance upon first filling.

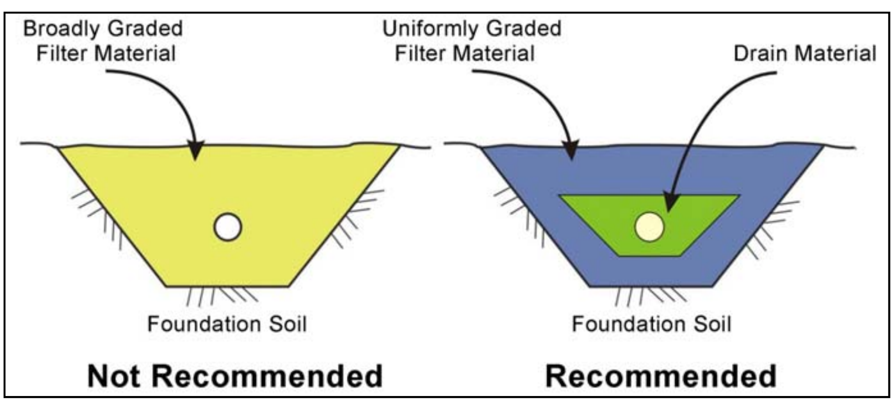

Figure 5.2.3.2-1.—Typical one-stage (left) and two-stage (right) toe drains in a trapezoidal trench.

While toe drains transfer and discharge seepage away from the dam, they also are important features for the monitoring of embankment dams. Monitoring of dams is important because as dams age, their performance may change. A design flaw or mistake made during construction can go undetected for years, or even decades, and monitoring will aid in the long-term performance of the structure. Toe drains permit three key observations in such a monitoring program: flow measurement, detection of cloudy seepage, and sediment (soil particle) accumulation. All three can be achieved in an inspection well installed either at the discharge end of the toe drain or along the toe drain alignment. An inspection well generally consists of a flow measurement device (either a weir or a flume) and a sediment trap upstream of the measurement device. Details of toe drains and inspection well configuration can be found in appendix E.

Self-propelled video cameras can be used to examine and record the condition of drainpipes. Video surveys are invaluable during construction and periodic dam safety examinations. Due to cable length and tractive ability of the unit, access locations along the drain should not be greater than 500 feet. If turns or large grades are present, this distance may need to be less. Angles through fittings should not be greater than 22.5° for camera and cleaning equipment access [40].

Drainpipe should be laid at a uniform grade without sags or bends. Sags can lead to the pipe flowing full through the sag, which can lead to recharge of the foundation and backing up water into the section prior to the sag. When drainpipes are constructed on soft, heterogeneous foundations, differential settlement may occur, which can also lead to sags. If such conditions are expected, the pipe size should be increased so that the calculated flow depth is no more than 25 percent of the pipe's interior diameter.

As described in the following sections, toe drains can be constructed utilizing several different geometries and construction methodologies. The type of configuration that is used is dependent on the expected amount of seepage. Two types of trench geometry used are rectangular and trapezoidal cross sections. Rectangular trenches with vertical side slopes are typically used where seepage is expected to be small. Trapezoidal trench sections are used where larger amounts of seepage are expected.

A condition that should be considered when toe drains are added to or replaced in existing dams is the potential for an increase in gradient under the dam. At sites where hydrostatic pressure is near or above the ground surface, the addition of a toe drain will decrease that pressure. However, it should be noted that the differential head between the reservoir and downstream toe will increase. This increase in differential head will lead to an increase in gradient through the foundation and subsequently increase the chance for particle movement over existing conditions.

5.2.3.2.1 Vertical Versus Trapezoidal Trenches

As previously stated, toe drain trenches may be designed with either vertical sides or sloping sides as shown in figures 5.2.3.2.1-1 and 5.2.3.2.1-2. Safety considerations will limit how deep a vertical trench can be excavated if construction workers and other personnel are required to enter the trench. Trenches having vertical side slopes are less expensive since they require less excavation and processed backfill. Complications exist for the construction of two-stage toe drains in small spaces. One method used to eliminate such problems is the use of a "dog house" form that allows the introduction of the filter and drain material separated by a moveable form as shown in photo 5.2.3.2.1-1. Note that care needs to be taken to place sufficient material under the haunch of the pipe in order to provide adequate support.

As indicated by the photographs in photos 5.2.3.2.1-1 and 5.2.3.2.1-2, the trapezoidal cross section permits for a deeper toe drain installation and a greater surface area of drainage material for interception of water flow through the foundation. Therefore, the trapezoidal section will provide a more robust method of flow interception for sites with seepage concerns.

Photo 5.2.3.2.1-1. Rectangular cross section foundation trench drain with gravel filter (envelope) surrounding perforated collector pipe and fine sand filter in primary part of drain. Boxes are contractor's innovative idea of placing the coarse filter around the pipe. By closing the top of the box, fine drain fill can be placed and kept separated from the coarse drain zone.

Photo 5.2.3.2.1-2. Trapezoidal foundation trench drain at toe of embankment. Coarse inner filter (envelope) surrounds perforated collector pipe, and the fine filter provides filter compatibility with foundation souls.

5.2.3.2.2 One-Stage Versus Two-Stage Design

Historically, toe drains have incorporated one-stage and two-stage designs as shown in figure 5.2.3.2-1. One-stage designs are used when small amounts of seepage are expected. Two-stage designs are used when a large amount of seepage is expected. Incorporation of a perforated drainage pipe to facilitate flow is almost always done on a two-stage design. Collecting water in a toe drain system is not always easily accomplished, and attention should be paid to how water flows through the system [10]. Additionally, design of filters placed on foundation soils is complicated by a greater variability of those materials than core material or other engineered fills. Gradation of a toe drain should be checked to make sure the filter will not act as a barrier to any foundation units. Such barriers do not provide sufficient pressure relief, and in situations where an existing dam is being modified, pressures may increase.

5.2.3.2.3 Collector Pipes

Collector pipes have a long history of poor performance in embankment dams. Earlier materials such as clay, concrete, and corrugated metal pipe (CMP) have had poor strength and/or joint performance and/or corrosion. Pipe junctions have also been an issue since no manufactured products existed during this era, and the junction was usually made by a “field fit.” Photo 5.2.3.2.3-1 illustrates such a junction for a “Y” connection in clay tile pipe. Plastic pipe has also been used, and while its performance has been better, it has not been without its problems. Some polyvinyl chloride (PVC) products were brittle and did not withstand the rigors of heavy construction, and aging [10a] has been an issue with some high-density polyethylene (HDPE) products.

In the last two decades, corrugated HDPE pipe was a popular choice for Reclamation toe drain construction. In the late 1990s, video examination of Reclamation toe drains showed that a number of these installations were exhibiting some form of distress, ranging from minor deformation to complete collapse. Most of these cases were single-wall corrugated HDPE, which has been found to experience strength loss with time. Due to the high number of structural failures and lack of laboratory data on the strength of perforated versus nonperforated plastic pipe, Reclamation undertook a study to evaluate these products [11]. That study found that perforated corrugated pipe (PVC or HDPE) had the same load carrying capacity as nonperforated pipe since the strength of the pipe comes from the outside corrugations, which are not perforated. The study also demonstrated that perforated solid pipe has a diminished strength in relation to nonperforated pipe and showed that some PVC products are brittle. The report also addressed installation issues, commonly available perforation sizes, and joint types for the different products. Since failure of pipes that were designed based on static conditions (overburden) has occurred, it is thought that construction loads are the more critical loading condition.

Joints for corrugated HDPE and PVC pipes are typically bell and spigot or butt joint with a collar. Gaskets are available for most of these joint types so they are watertight. The greater concern is proper field installation. If pipe ends or couplers are damaged or get dirty prior to connection, marrying the pipe segments in the field can be difficult. Frustrated workers may struggle with a pipe connection and give up prior to the joint being completely closed. Recent video inspections have shown that poor joint connections are as much of a problem as crushing in the central section.

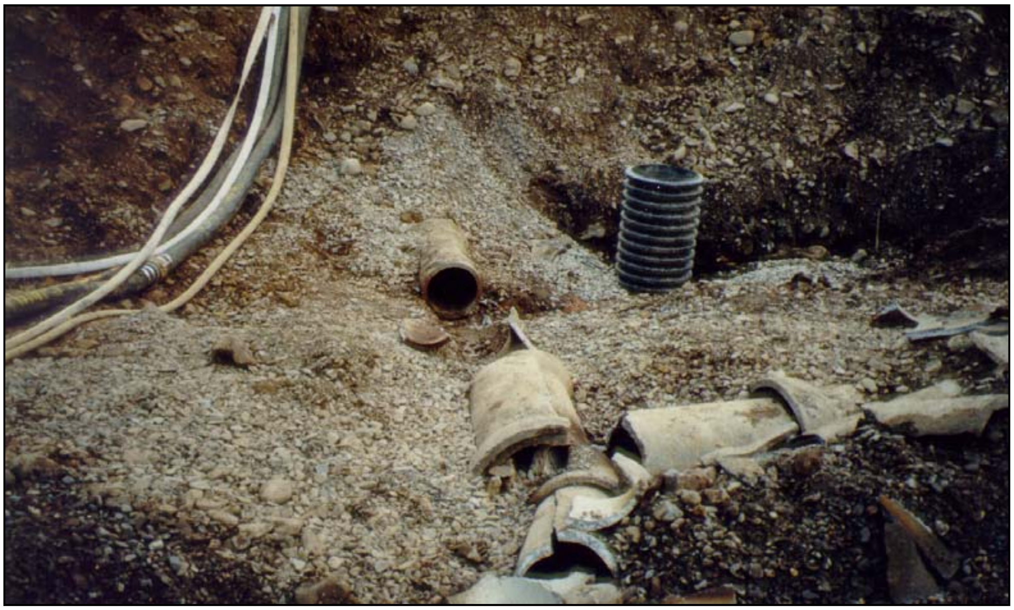

Photo 5.2.3.2.3-1. 1950s era concrete pipe used as a toe drain. Water enters the pipe through a gap left in the bell and spigot joints. A "Y" junction is shown with two laterals that connect to a trunk line shown on the right side of the photo. Since connectors were not manufactured for this configuration, pieces of broken pipe were stacked together, making a protective cap for the junction. This junction was exposed during excavation for a toe drain replacement.

Taking these factors into account, profile[10] HDPE pipe is recommended for use in toe drain applications. The advantages of this pipe type over all others are:

- Large load carrying capability.
- When a load carrying capability much greater than that needed for overburden is used, the pipe is more likely to withstand poor or incorrect installation methods.
- Joints are field welded, strong, and watertight.
- Junctions are factory welded, strong, and watertight.

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[10] Profile pipe is the typical pipe geometry with a smooth interior surface and smooth exterior surface.

- Aftermarket perforations can be used, allowing the designer to specify the perforation size and permitting more flexibility in the selection of gravel envelope material.

At a minimum, perforated collector pipes should always be inspected by video camera at the end of construction to verify that no damage occurred during installation. Historically, a second method has been used to inspect toe drain pipe that consists of pulling a ball or torpedo-shaped object through the pipe. While this method can be used, it should not be the sole source of installation acceptance since the method is easily cheated.

Almost all perforated collector pipes that have been in service for a period of time will have some amount of material in the pipe invert or contain some kind of clogging in the perforations consisting of algae, roots, or sediment. Since power washing is now commonly available, it is possible to flush out such pipes. Before doing so, consideration should be given to whether the pipe will be damaged or an erosion condition aggravated. If the drainage system design is of high quality, then cleaning can be used. If the drains are of poor or unknown quality, cleaning should be avoided since the system may have "self-healed" to a stable condition, and cleaning it could reactivate material movement.

5.2.3.3 Relief Wells

In a foundation where a pervious layer is overlain by an impervious layer (or stratum), the pervious layer may contain high pressures or artesian conditions. This can lead to blowout of the overlying impervious layer (aquitard). In these situations, it may be impractical to construct a toe drain down to the pervious layer, especially if it is a significant depth (> 20 feet). In such cases, pressure relief wells can be used. Relief wells are constructed with well screens, much like a water well, with an annular space surrounding the well screen containing a designed filter pack. Relief wells are usually outletted to the ground surface or to a discharge pipe below the surface. It should be noted that the particle retention criteria for well design may differ from what is presented in this design standard. Typically, well design criteria are more strongly influenced by permeability requirements.

Relief wells have a distinct disadvantage in that they require ongoing maintenance to rejuvenate their flow capacity. Iron ochre and chemical incrustations are a plague to relief wells, and the cost to maintain their capacity must be factored into a life cycle cost for their use. Due to this maintenance issue, as well as the ineffectiveness of wells intercepting 100 percent of foundation flows, toe drains are preferred as the pressure reduction measure for shallow applications.

5.2.3.4 Slurry Trench Filters

As described previously, when drainage or filtration is required at the downstream toe of a dam, a high water table or confined aquifer can make filter/drain installation difficult in open excavation. Another method used to install a filter and/or drain is the slurry trench method. The use of a slurry trench seems counterintuitive since slurry trenches are often used to construct cutoff walls through dams. The use of a bentonite slurry is also contrary to constructing a drainage element that provides high permeability relative to the surrounding foundation. To overcome these obstacles, a slurry trench method was developed using a degradation technology [12, 13]. In this method, a synthetic biopolymer or other organic admixture, such as guar gum, is used in place of the bentonite admixture used in more common slurry applications. These admixtures are mixed with water to produce a slurry that stabilizes the trench long enough to place the filter or drain backfill. Biodegradation of the slurry then occurs, permitting the trench to act as a flow interceptor. Shortcomings of this method include the inability to visually inspect the trench, or to compact the backfill.

5.2.3.5 Modification of Existing Drainpipes

Many existing dams have seepage issues related to misunderstood site conditions, poor design, poor construction techniques, or a combination of all three. Adding to these problems can be the inclusion of improperly designed drainage features. For several decades, toe drains consisted of butt joint pipe surrounded by coarse gravel as shown in photo 5.2.3.5-1. The gravel seldom met particle retention criteria for the foundation soils, and separation between the pipe joints was seldom properly controlled, thus permitting passage of finer grain soil through the gravel backfill. These conditions have resulted in active piping through the drainage system on plugging of the toe drain as happened at Lake Alice Dam in Nebraska.

Photo 5.2.3.5-1. Clay tile pipe surrounded by gravel-size material. Note mechanical pencil for scale. Surrounding the gravel is a mixture of silt and sand backfill that does not meet filter criteria for the gravel. Seepage enters the pipe through joints between pipe segments. The silt and sand can erode through the gravel backfill and enter the pipe through the joints.

Additionally, older drainpipes do not have sufficient strength and will be cracked, deformed (see photo 5.2.3.5-2), or completely collapsed. When the pipe begins to fail, this leads to greater amounts of material entering the pipe and rendering many systems completely clogged with foundation material as shown in photo 5.2.3.5-3.

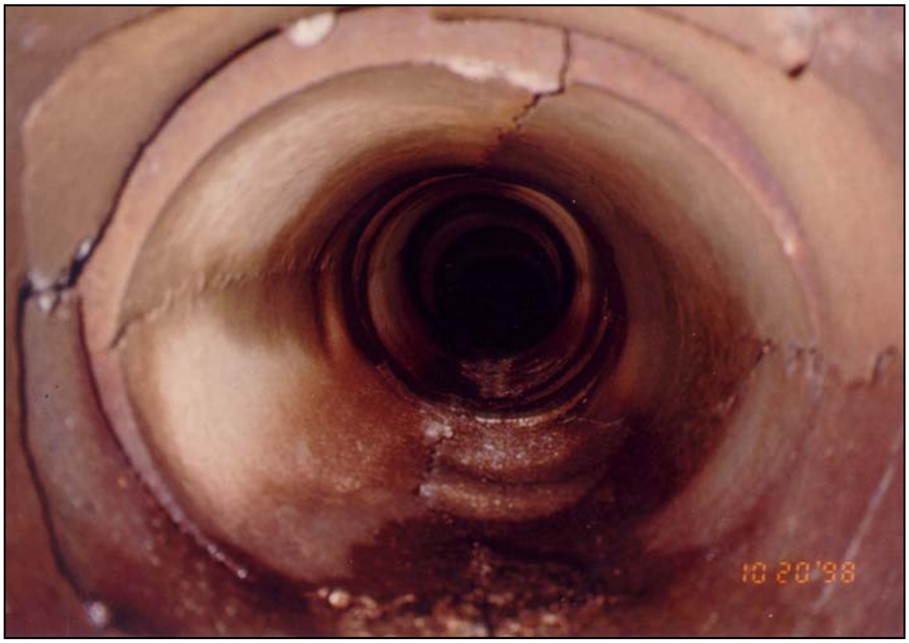

Photo 5.2.3.5-2. Interior view of a reinforced concrete pipe from the 1950s. Note that the pipe is overstressed, and cracks have formed at the crown and spring line. The pipe has also deformed to an oval shape. In the foreground, a joint can be seen and sand that passed through the joint.

Since many toe drain installations were installed with no consideration given to future examination, video investigations can be complicated. Since “turns” were typically installed, video cameras are not able to get past those points. Also, if the drain was clogged with material, or crushed, examination is not possible. Vegetation could also lead to problems with existing drainpipes. As a concentrated source of water, drains are attractive to plant roots. In extreme cases, root growth can completely clog a pipe, greatly reducing its flow potential as shown in photo 5.2.3.5-4.

Typically, a deficiency is identified for the situation described above, and a safety of dams modification is undertaken. Repair of existing drains is uncommon, and total replacement is the more usual course of action. When replacing existing drains, consideration should be given to the amount of flow collected by those drains. While the pipe itself is in poor condition, and particle retention criteria are not met, these conditions can result in attractive interception of ground water flow at the expense of particle retention. Replacement of drains with a one-stage filter that meets particle retention criteria, can result in significantly less interception of seepage. This, in turn, can result in higher pressures and, possibly, seepage from the ground surface—a situation that did not occur prior to the repair.

Photo 5.2.3.5-3. Clay tile pipe from 1916 as it was exposed during excavation. Note that the pipe was completely clogged with silt and sand.

Photo 5.2.3.5-4. During modification of a dam, this toe drain pipe was exposed during excavation. The pipe was completely clogged with the root ball shown in the foreground. It was noted that a tree was growing over the toe drain, and the drain was probably a water source in this arid region of central Oregon.

5.2.4 Types of Filters

The term "filter" has been used to describe an engineered material that provides a number of functions in an embankment dam. These functions can range from protecting core material from migrating into a coarser shell material to the collection and filtering of seepage in a pervious foundation. The "filter" required for each of these functions will require different material gradations. As described previously, when designing a filter, consideration is given to two criteria—preventing particle movement and permeability (drainage). Filters used in different locations within a dam place different demands on these two criteria. Following is a description of four filter types, or classes, related to the function they perform in embankment dams:

- **Drainage filters (class I)**.—A filter whose purpose is to intercept and carry away the main seepage within a dam and its foundation. These filters may have to remove large amounts of seepage for dams on pervious foundations or dams of poor construction. The filters consist of uniformly graded materials, typically in two stages. The filter must meet the requirements for both particle movement and drainage. Toe drains typically fall into this class.

- **Protective filters (class II)**.—These are filters whose purpose is to protect base material from eroding into other embankment zones and to provide some drainage function in order to control pore pressure in the dam. These filters are typically uniformly graded and in several stages, but they can also be broadly graded to reduce the number of zones to make the transition to the base material. This class includes chimneys, blankets, and transition zones on the downstream side of the impervious zone of the dam.

- **Choke filters (class III)**.— Filters whose purpose is to support overlying fill (the base material) from moving into pervious or open work foundations. These filters are typically broadly graded and only have a requirement to stop particle movement. There is no permeability requirement. Choke filters may be used under upstream impervious blankets that overlie pervious foundations. Choke filter material is also used in emergency situations in an effort to plug whirlpools and sinkholes.

- **Crack stoppers (class IV)**.— The function of this type of filter is to protect against cracks that may occur in the embankment core, especially caused by seismic loading and/or large deformations. Strictly speaking these are not filters as described in this design standard although many of the same principles apply. The dimensions of this class of filter are controlled by expected displacement (horizontal or vertical). While there is no permeability requirement for this type of filter, it should be relatively free of fines so that the crack stopper itself does not sustain a crack. Due to cementation, it may not be practical to obtain an uncrackable first stage filter (sand), so a second stage (gravel) filter may be required. Second stage filters may also be required for transition to a coarser shell material. This class of filter or transition zones can be used either upstream or downstream of the core. Their use is recommended when significant seismic loadings are present.

A summary of these filter classes and their requirements is given in table 5.2.4-1. The stage, gradation, and permeability issues are described in more detail later in this design standard.

Table 5.2.4-1. Filter classes and their uses and requirements

Class	Filter type	Uses	Multiple stages required?	Uniform gradation required?	Permeability/ drainage required?
I	Drainage	Toe drains, relief wells, drain fields	Yes	Yes	Yes
II	Protective	Downstream chimneys, blankets, transition zones	Frequently	No	Yes
III	Choke	Foundation filters, sinkhole backfill	No	No	No
IV	Crack stopper	Upstream and downstream chimneys	Frequently	Yes	No (although the filter should not sustain a crack)

5.2.5 Adding Filter Protection to Existing Conduits

Many existing dams, both large and small, were originally constructed with outlet works or other conduits without filter protection. If a dam safety issue has arisen due to poor performance of an existing conduit, or a chimney filter is being added to an existing embankment, adding a protective filter around the conduit is frequently warranted. This section will focus on outlet works or other types of conduits, such as spillway conduits, that were constructed on unconsolidated deposits (soil) and then covered with embankment fill. These conduits are typically constructed in one of two ways: (1) cut and cover if they are constructed below existing grade and (2) at grade if they were built on the existing ground surface.

Conduits on soil foundations require filter protection around the entire conduit. Exposing a conduit and adding a filter to only the sides and top will leave the foundation under the conduit unprotected. Piping channels can form under conduits, and it is an ideal location for such development because the conduit will act as a roof for the piping channel. A reliable method for filter placement under a conduit is also needed because any gap or low density areas will render the protection useless. Some methods have been proposed for addition of a filter under a conduit that are considered unacceptable. Those methods are summarized in table 5.2.5-1. When conduits are founded on rock, no filter is required under the conduit. In a similar manner, conduits founded in rock trenches where the bottom and side or sides of the conduit are poured against the rock, filters are not needed in those locations.

Table 5.2.5-1. Unacceptable methods for adding filters under conduits

Method	Discussion
1. Excavating under half of the conduit and backfill with filter material. Next, excavate and backfill under the other half.	Filter material cannot be compacted sufficiently to prevent settlement once the water table rises.
2. Cut out a section of conduit floor, place filter, replace floor.	Since reinforcement will be cut in reinforced concrete conduits, the hoop strength of the conduit will be lost.
3. After placing the filter using one of the above methods, grout from inside the conduit to fill any voids between the bottom of the slab and top of the filter.	Grouting operations should never be carried out adjacent to filters because they can become contaminated with grout, rendering the filter useless.

In the interest of providing intimate contact between the filter and the bottom of the conduit, a section of the conduit should be removed and reconstructed after filter placement.

5.2.5.1 Location of Filter Around Conduit

Two locations are generally used for adding a protective filter around existing conduits: the preferable location is near the centerline of the dam, but locations near the downstream toe are also acceptable. The centerline location is preferable since the greater overburden stress will provide greater confining stress that will keep the filter in contact with the conduit and will have greater resistance to hydraulic fracturing. Adding filter protection near the centerline of the dam will require removal of a significant portion of the embankment, including the crest, and drawing the reservoir down would be required. If reservoir operation is to be maintained during construction, this method may not be acceptable. A cross section of a typical filter addition near the centerline of a dam is shown on figure 5.2.5.1-1.

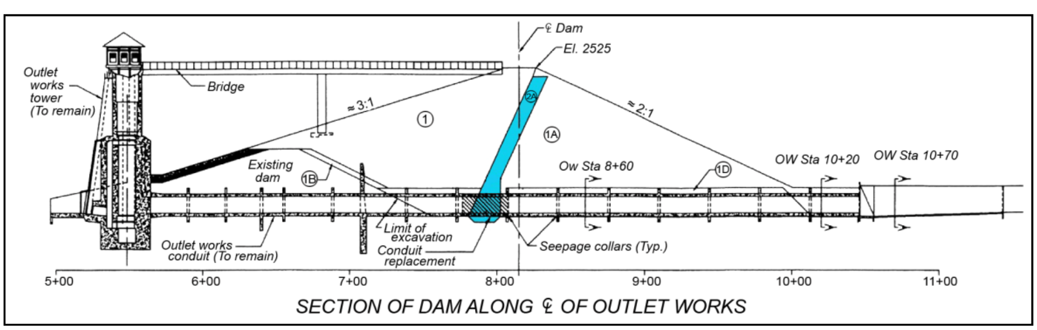

Figure 5.2.5.1-1. Typical filter addition around a conduit near the centerline of a dam.

Diaphragms can also be added to downstream locations, but sufficient overburden is required to overcome any "blowout" concerns. Assuming a seepage path exists along the existing conduit and full reservoir head is expected at the filter diaphragm, sufficient overburden is required to overcome the hydrostatic pressure. This can be accomplished by placing a stability berm at the downstream toe over the filter diaphragm. Assuming the density of the berm is twice the density of water, the berm height could be up to one-half of the reservoir height. A cross section of a typical filter addition near the downstream toe of a dam is shown on figure 5.2.5.1-2.

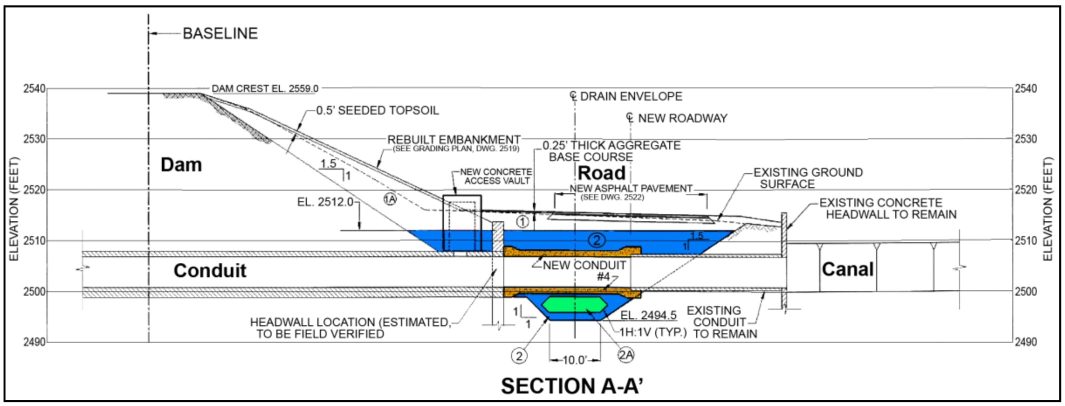

Figure 5.2.5.1-2. Typical filter addition around a conduit near the downstream toe of a dam.

Acceptable construction methods for the addition of a filter diaphragm around an existing concrete conduit on a soil foundation are included in table 5.2.5.1-1. The procedures would be similar for other conduit types, although the addition of a cradle may be required.

Table 5.2.5.1-1. Acceptable method for addition of a filter to an existing conduit on a soil foundation

Step 1	Excavate around the conduit, exposing it in the area of filter placement.
Step 2	Sawcut through the conduit and demolish between the sawcuts.
Step 3	Excavate into the foundation under the conduit profile a minimum of 2 feet. The trench width (measured upstream to downstream) should be greater than 6 feet. The upstream and downstream side slopes should be 2H:1V or flatter. An offset of at least 1 foot should be used between the top of the excavation slope and the sawcut face.
Step 4	Inspect and accept foundation. Proof roll the foundation.
Step 5	Place the filter material in the bottom of the trench and compact. Check the filter density with an inplace density test.
Step 6	Rebuild the conduit.
Step 7	Replace fill, including filter diaphragm around conduit. Construct stability berm if required.

5.2.5.2 Minimum Dimensions for Filters Added to Existing Conduits

The minimum dimension for the addition of filter protection around existing conduits is a function of the conduit size and whether or not seepage collars are present. For conduits that do not include seepage collars and have an **inside** diameter of 2.5 feet or less[11], filter protection should generally extend three pipe diameters around the sides and top of the conduit and 1.5 pipe diameters below the conduit. The filter thickness (measured upstream to downstream) should not be less than 3 feet.

Since internal erosion failure modes along conduits are based on flow along the outside of the conduit, the previous rules should be based on the **outside** or maximum structural dimension. If the pipe is encased in concrete, or the pipe is set in a concrete cradle, the outside dimension of the concrete should be used. For conduits larger than 2.5 feet inside diameter that do not include seepage collars, the minimum extent of filter protection should be at least 8 feet for the sides and top and 4 feet under the conduit. The filter thickness (measured upstream to downstream) generally should not be less than 8 feet. The larger dimensions for the larger size conduits are primarily based on the equipment needed to construct these features.

For existing conduits that include seepage collars, regardless of conduit size, the extent of filter protection is defined by the size of the collar. In these cases, the filter extent should generally not be less than 8 feet beyond the limit of the sides and top of the seepage collar. The filter should extend no less than 4 feet below the bottom extent of the collar. The intervening space between the outside of the conduit and the outside edge of the seepage collar should also be filled with filter material. This section also assumes that the existing conduit is founded on soil deposits. For cases where the conduit is founded on rock see section 5.2.5.

Example: A 6-foot inside diameter reinforced concrete conduit has an exterior horseshoe shape. The lateral external structure width is 8 feet. The structure includes seepage collars that extend 4 feet beyond the outside shape of the structure. That is, the extent of the seepage collars mimics the outside shape of the structure on the top, sides, and bottom. For this case, a diaphragm filter with the following dimensions would be used:

Side	Extent beyond seepage collar: 8 feet
	Extent beyond side of structure: 8 + 4 = 12 feet
Top	Extent beyond seepage collar: 8 feet
	Extent beyond top of structure: 8 + 4 = 12 feet
Bottom	Extent beyond seepage collar: 4 feet
	Extent beyond bottom structure: 4 + 4 = 8 feet

[11] It is assumed this size of conduit is a pipe. Larger conduits discussed later are typically structures such as reinforced concrete outlet works conduits.

5.3 Design Principles

5.3.1 General

When designing filters and drains it is important to consider both particle retention and drainage. The "filter criteria" given in this chapter are for elements where filtering (particle retention) is the primary need and pore pressure or head buildup is not likely to be of any consequence.

When flow in an element must take place without the buildup of appreciable head, designers should make estimates of all quantities of seepage that will need to be removed using chapter 8 of this design standard – Seepage, as well as appendix A [14, 8, 15]. Designers should analyze the entire drainage system and make sure all seepage can be adequately discharged through the entire system.

The criteria presented in this chapter are developed from Terzaghi, supplemented by controlled laboratory tests and studies performed by Bertram [16]; Reclamation [17, 18]; USACE Waterways Experiment Station [19, 20, 21]; Soil Conservation Service [22]; Sherard, Dunnigan, and Talbot [23, 24], Sherard and Dunnigan [25], and Fell and Foster [26].

The gradation range of base soil (protected soil) and protective filter/drain should be plotted on a Gradation Test form (figure 5.3.1-1). A blank example of the form is shown in figure 5.3.1-2. It is desirable to plot each gradation curve from all samples from a base material on the same sheet. For example, plot on one sheet all gradation curves of material that are to be used for an impervious zone. The typical range of the impervious material, as well as outlier gradations (gradations that do not fit within the typical range), can then be seen. The filter/drain is usually designed to protect the typical range of the base soil[12]; criteria do not necessarily need to be met for all outliers. If the filter/drain is for protecting a foundation soil, the designer may have to choose the range of foundation materials to be protected. This is discussed in more detail in section 5.4.1.

It is also beneficial to plot all gradation curves available from exploration of specific filter/drain borrow sources on a single sheet and compare the required filter/drain gradation to gradation ranges of available material on that sheet. A final plot should show the range of protected soil, range of filter material, and range of drain material all on the same sheet (see the design example provided in appendix C).

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[12] See section 5.4.1 for additional discussion.

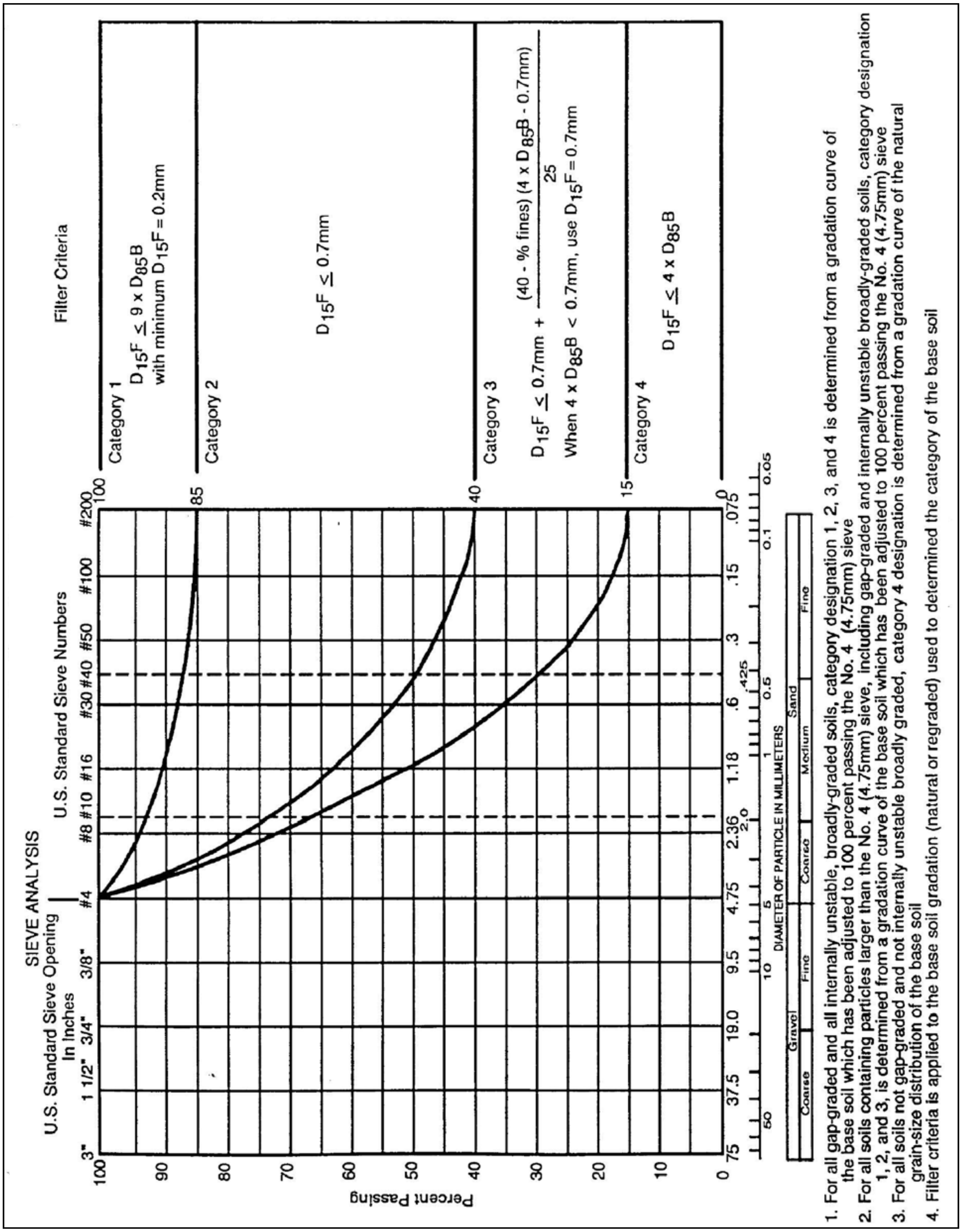

Figure 5.3.1-1. Graphical representation of categories of base soils (see section 5.4.3 for a description of base soil categories)

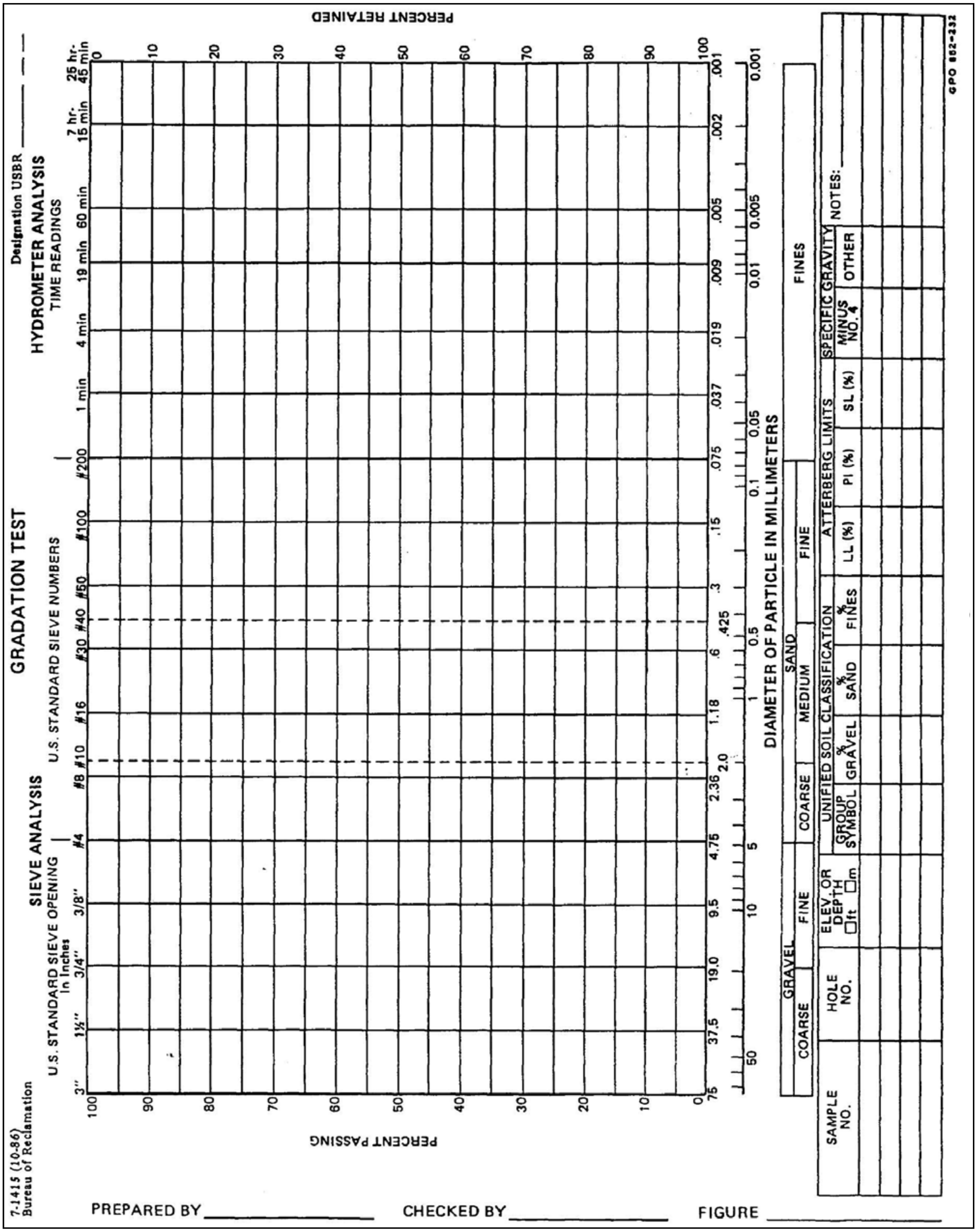

Figure 5.3.1-2. Gradation Test form.

The designer should realize that even with the ratio of $D_{15}E$ to $D_{85}F$ set at 4, some movement of fines[13] from the first-stage filter into the second-stage filter (gravel drain) may occur and could result in contamination of the second stage. This is especially true if criteria for uniformity of the filter or drain are not met. This contamination is likely to occur at changes in slopes, such as at chimney-to-blanket transitions. Thicker zones and/or additional drainage features should be considered. Also, a laboratory test should be performed to check whether the filtering capability of the drain is adequate, and analyses should verify that the gradients in the filter/drain are not excessively high. It should be noted that it can be difficult to select D_{15} for coarse filters. In such cases, the grain size from the next lowest sieve can be substituted for D_{15}. The grain size curve of a filter does not have to be parallel or similar in shape to the grain size curve of the base material (protected material). Generally, a filter should be uniformly graded to provide adequate permeability and prevent segregation during processing, hauling, and placing. However, it should be noted that well-graded gravelly sand can be an excellent filter for a very uniform silt or fine, uniform sand if segregation is avoided in placement.

To help ensure adequate permeability in the filter, the percentage finer than the No. 200 sieve for filters must not exceed 5 percent by weight after compaction (2 percent stockpile, 5 percent in-place after compaction). Generally, the additional reduction in fines content may be necessary to increase permeability and reduce filter cracking potential. The permeability of a filter should be at least 25 times that of the base material. This criterion is generally met if $D_{15}F$ is larger than 5 times $D_{15}B$. The permeability (k) of uniformly to moderately graded sand and gravel filters (coefficient of uniformity [C_u] generally 1.5 to 8) can be estimated by the empirical equation:

$$k = 0.35\ (D_{15}F)^2$$

where:

k is in centimeters per second, and $D_{15}F$ is in millimeters [23, 24].

Also, other empirical relations using grain size can be used to estimate permeability, such as the NRCS Soil Mechanics Note 9 (SM-9, March 1984) and Cedergren [14].

5.3.2 Precautions

In applying filter design criteria, the designer should remember that the criteria were determined in the laboratory under controlled, virtually ideal conditions.

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[13] These fines are what remain from the washing operation or particle breakdown from placing and compacting operations.

These same conditions may not be matched by conditions in the field; moreover, careful attention to achieve isotropy and homogeneity in the laboratory cannot be matched in the field, either in the construction of the filters or the base material. Further, as soon as the structure is placed in operation, the assumptions around which the elements are designed begin to deviate further and further from field conditions as weathering starts, sedimentation begins, bacterial growth occurs, deposition or removal of soluble solids begins, and corrosion or deterioration begins. These changes in conditions are difficult to evaluate in filter design and might be called judgment factors that would cause the designer to modify the criteria to fit anticipated field conditions during operation. Conservative designs are prudent.

If the designer has any doubts concerning the filter's performance, filter tests should be conducted. For example, dispersive soils, very fine grained cohesionless soils, highly plastic soils, and soils prone to desiccation may require extra precautions. The criteria presented are considered adequate for these types of soils; however, filter tests with the base soil and filter are still prudent. The methodology presented in section 5.6.1.1 is recommended as guidance for testing the base soil and filter for fine grained, problem soils. Material quality should also be examined as described in section5.6.2.

When designing toe drains or other drainage collection systems for pervious foundations where seepage is expected to be large, consideration should be given to the permeability of the filter in relation to the permeability of the foundation as described in appendix A. In situations where the foundation consists of interbedded silts, sands, and gravels, the designer may elect to size the filter for the silt sizes. This can result in a filter composed primarily of sand sizes being placed over the gravel layers that carry the majority of seepage. This filter then acts as a barrier to the flow in the gravel, resulting in poor seepage collection and high pore pressures. If this issue cannot be resolved by adjusting the filter design (or improved drainage), additional water barrier elements (i.e., a cutoff wall) may be required.

For economy and simplicity, single stage drainage elements are sometimes considered. These drainage elements are a combination of sand and gravel and are placed directly around the drainpipe. When evaluating this type of filter, consideration should be given to internal stability (section 5.3.8) and plugging of perforations within the drainpipe (see section 5.5.2 for a discussion of perforation plugging). The designer should also be aware that a broadly graded sand and gravel filter may have a lower permeability than a uniformly graded sand filter. Typically, two-stage filter/drain combinations have higher permeability and are more efficient in collecting seepage than single stage filters.

5.3.3 Cost

The design of a filter should result in the minimal cost necessary to satisfy the requirements of the application and provide for reasonable anticipated construction methods. If natural deposits are suitable and can be economically processed to obtain sufficient materials, they should be used to produce the filter and drain material. Sizing of filter and drain zones should provide a balance between ease of construction and available material quantities while meeting hydraulic requirements.

Another cost topic is single stage versus two stage (or greater) filter/drain systems. For some projects, a single element may serve as both filter and drain. In others, certainly including more critical and probably larger projects, two stage systems are appropriate.

A number of factors control the cost of a filter/drain system including commercial availability versus dedicated processing, volume of material required, haul distance, standard versus customized gradation, and placement method. In the early stages of the design, the engineer should determine the availability of commercially produced aggregates and their distance from the work. A number of standard specification aggregates may meet the gradation requirements for filter and drain materials as described in section 5.7.2. One of the most popular is so-called "concrete sand," otherwise known as American Society for Testing and Materials (ASTM) C 33 fine aggregate. (Note: the fines content of the standard specification will need to be lowered.) Obtaining commercially available standard aggregate typically results in the lowest cost for the material. For additional discussion on this topic, see Section 5.7, "Material Sources."

If the job is large and commercial sites are far from the work, or a "custom" gradation is required, onsite processing may be the most economical. Due to the number of variables, a borrow utilization study would be useful to evaluate whether onsite processing or a commercial source is more economical.

Construction methods should be considered when designing the filter. Reducing cost by using narrow filter/drain zones to minimize material volumes may appear attractive; however, higher costs resulting from increased effort for placement may cancel any savings. Earlier studies conducted in 2001 indicated commercially available material within 15 miles[14] of the dam can be placed most economically in a minimum 8-foot-wide zone. As haul distance increases and job size decreases, narrow zones become more attractive.

For larger jobs that use dedicated processing, consideration should be given to the various materials for production from the plant and their use within the design. For example, for a given processing plant operation, equal amounts of filter and drain material are produced, but a greater volume of filter is required in the work, leaving some drain material not used. The design could be adjusted to increase the amount of drain material while reducing the amount of filter. Excess drain material could also be used for other features such as slope protection and riprap bedding.

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[14] Fuel prices that differ from those in 2001 will influence the break point.

5.3.4 State of the Art

Because filters and drains are vital to the safe performance of hydraulic structures, they have been the subject of fairly extensive research [23, 24, 25, 28, 29, 30, 31, 32]. This research is included in this design standard for completeness, and since some of this work has not been proven by field application, this standard does not endorse it.

In the 1980s, a filter criterion was developed [33] that confirmed Terzaghi's relationship of $D_{15}F/D_{85}B$ but added a requirement in the relationship of $D_{95}B$ to $D_{15}F$. This additional requirement addresses internal stability, which is discussed in section 5.3.8.

Significant work has been undertaken at the University of New South Wales [34, 35] related to studies of risk associated with embankment failure modes. This work examined partial erosion and continuous erosion boundaries for increasingly coarse gradation of filter against a number of base materials. The conclusion of the study is that current criteria are adequate to ensure that no erosion initiates. Some discussion is presented about filter compatibility between zones in existing dams, and the reader may find this of interest, especially when considering partial or continuous erosion in existing structures.

The criteria presented herein, which are based on the traditional Terzaghi filter criteria and laboratory testing done by the Soil Conservation Service [23, 24], are considered adequate, easier to use, and have a performance record not available for recently proposed design procedures. In the last decade, Fell [32, 33] has performed followup research to that done by Sherard and examined dispersive soils more completely. Due to the sensitive nature of protecting dispersive soils, criteria have been added to the procedure. Hence, for the present, these criteria will serve as the basis for Reclamation designs.

5.3.5 Material Quality

Durability and material quality go hand in hand. Concerns with these characteristics are associated with breakdown during construction or long-term degradation. After leaving the processing plant, soil particles can break down during handling and placing procedures. Loaders and dozers place these materials in stockpiles in order to build larger piles, which are loaded into trucks, dumped onto the fill, bladed to a uniform lift thickness, and compacted by a smooth drum roller. Each of these operations can cause individual aggregate particles to break down. This breakdown leads to a change in gradation between the material produced at the plant and what is in place in the dam. Typically, filters are required to have no more than 5-percent fines measured in the fill after compaction. Typically, breakdown between the stockpile and fill will be 1 to 2 percent. While it is beneficial to specify measurement in the stockpile for construction operations, testing of the fill should also be done to measure the amount of breakdown caused by placement operations. The amount of breakdown is a function of the durability of the raw material, whether crushing was used to produce the raw material, and the amount of handling between the plant and the fill. Breakdown is usually a greater concern for smaller grain sizes used for filters than it is for larger grain sizes, which are used for drain material.

Filter and drain materials should consist of clean, hard, durable, dense aggregate that is free of any undesirable coatings or films, and it should be tested in the lab to assess suitability for the application and the amount of processing needed to meet the specified grain size limits as described in section 5.6.

As a minimum, the raw material should meet the durability requirements of concrete aggregate as defined in ASTM C 33-02A. In addition to the quality of ASTM C 33-02A, the material shall be nonplastic. Plasticity shall be determined in accordance with USBR 5360 from the *Earth Manual*, Part 2 [1], on material passing the No. 40 sieve. Nonplastic material is defined as having a PI of zero as per the above procedure. Additionally, the material shall be free of cementing agents such as, but not limited to, carbonate minerals, gypsum, sulfide minerals, and sand-sized volcanic (pyroclastic) ash. Cementing is indicated by cohesive behavior of granular material. Cementing agents can be detected by checking for the reaction of the material to hydrochloric acid, as well as the tests described in section 5.6.2.

For small projects, it may not be feasible to determine aggregate quality by laboratory testing. In this instance, the engineer should consider the mineralogy of the parent material. Quartz-based aggregates have higher quality than aggregates that come from sedimentary rocks. For materials obtained from commercial sources, stockpiles should be examined for slope uniformity. Piles with irregular slopes or near vertical surfaces may indicate high fines content or, possibly, binders or cementing agents in the material.

In cases where available material is not equal to the durability requirements specified for concrete aggregate or the suitability of a source is not clear cut for any other reason, a test fill should be considered either during design or early in the construction to determine the amount of breakdown caused by processing, loading, hauling, placing, and compaction of the filter or drain material.

It is also generally recognized that pit run material will be of higher quality than crushed material. When the option is available pit run material is preferred over crushed products.

5.3.6 Gradation Uniformity and Permeability

Grain size distribution of any given soil will affect that soil's permeability. That is, a uniformly graded soil will generally have a greater permeability than a broadly graded soil when they have the same D_{10} size. This is because void space between sand particles in the uniformly graded sand is replaced by gravel particles in the broadly graded mixture as shown in figure 5.3.6-1. The left side of the figure illustrates spheres of two sizes representing a uniformly graded soil (example: coarse sand). On the right side of the figure, three larger spheres overlay the original figure and are shown in red. They represent the inclusion of gravel-size particles, making the soil broadly graded. The figure illustrates that the larger particles now replace previously available seepage space through voids, and that lost space has been highlighted in blue. Note that the figure has not been corrected for the larger particle's edge to edge contact with the surrounding particles. The elimination of void space in the broadly graded soil results in a lower permeability [10].

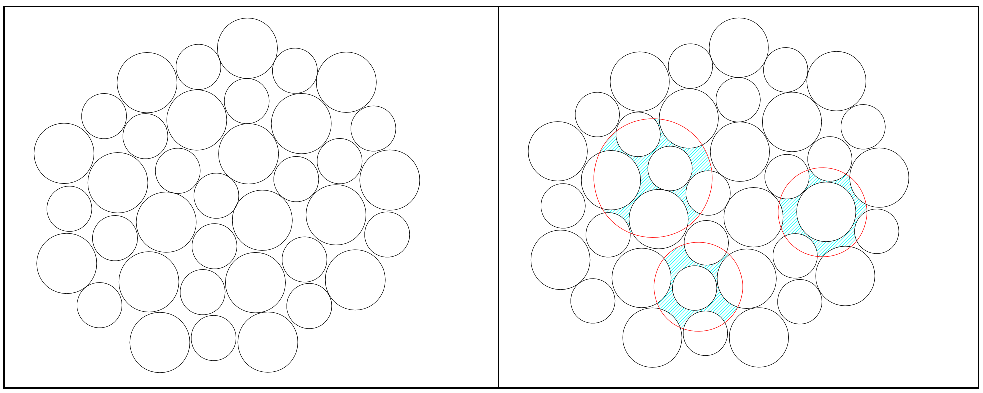

Figure 5.3.6-1.—The illustration on the left shows idealized spheres of two sizes and resulting void space between the spheres. For the illustration on the right, three larger spheres (red) are overlain on the original illustration. This demonstrates how the larger spheres will replace previously available void space, highlighted in blue.

5.3.7 Internal Instability

For the purposes of this design standard, broadly graded soils are defined as gravels with a $C_u \geq 4$ and a C_z between 1 and 3. Sands are broadly graded when $C_u \geq 6$ and C_z is between 1 and 3. These are the same definitions used in the USCS. As described earlier, the terms "broadly graded" and "well graded" as used in this standard are then equal.

There exist in nature some gap-graded and unstable, broadly graded base soils, usually graded from clay to gravel sizes, such as some glacial tills, that are internally unstable. In these types of materials, the fine portion of the soil may pipe through the coarse portion. If a proposed filter is designed based on the total gradation of the base soil, the filter will be too coarse, and the fines in the base soil may pipe through the filter. This occurred in the materials in the downstream section of Reclamation's Steinaker Dam, causing sinkholes to form in the downstream section of the embankment, shortly after first filling in the 1960s. For these types of soils, the filter should be designed to protect the fine matrix of the base soil rather than the total range of particle sizes. If filter design is based on the minus No. 4 sieve size of the base soil, as indicated in section 5.4.2, this problem is circumvented. Alternatively, several investigators have developed criteria for determining if a base soil is internally unstable, as well as filter criteria for these soils. The work of some of these investigators is summarized in the United States

Committee on Large Dams (USCOLD) publications, *Use of Granular Filters and Drains in Embankment Dams* [32] and *Similarity of Internal Stability Criteria for Granular Soils* [39].

Internal instability is the property of a soil whose void size exceeds the smallest grain sizes within the gradation. That is, the smaller soil particles can move and be redistributed into adjacent voids. Since this characteristic depends on the soil gradation, it is present in naturally occurring as well as processed soils. The results of research into internal instability are described in several technical publications [32, 39]. While research has focused solely on soil gradation, it appears that density, cementation, and loading (seepage or dynamic) are also important considerations in determining whether or not soil particles will undergo redistribution [34].

Internally unstable soils commonly will exhibit sinkholes as seen at Tarbela and Keechelus Dams. Sherard [40] surmised that some form of discontinuity or defect needed to be present in order for internal instability to be initiated. Such discontinuities include borehole riser pipes, buried instrumentation, zones of low density, and areas of high gradient. Figure 5.3.7-1 is an aid in identifying internally unstable soils. Sherard obtained data on a variety of soils that were judged to be internally unstable. He plotted a band [40] around these gradations as shown on figure 5.3.7-1. Soil gradations plotting within this band are potentially internally unstable. Another method to check for internal instability is to compare the slope of the gradation curve against a constant slope line of the relationship $D_{point1} < 4*D_{point2}$. This line is shown on figure 5.3.7-1 and is noted as “4x.” The slope of this line is the important aspect of it, and the location on the plot is unimportant. Any portion of a gradation curve that is flatter than this line indicates a potentially unstable soil, whereas portions of the gradation curve steeper than the line indicate a stable soil. This technique can also be used to evaluate gap-graded soils. Note that the slope of the 4x line is roughly equal to the boundary slopes of Sherard’s band.

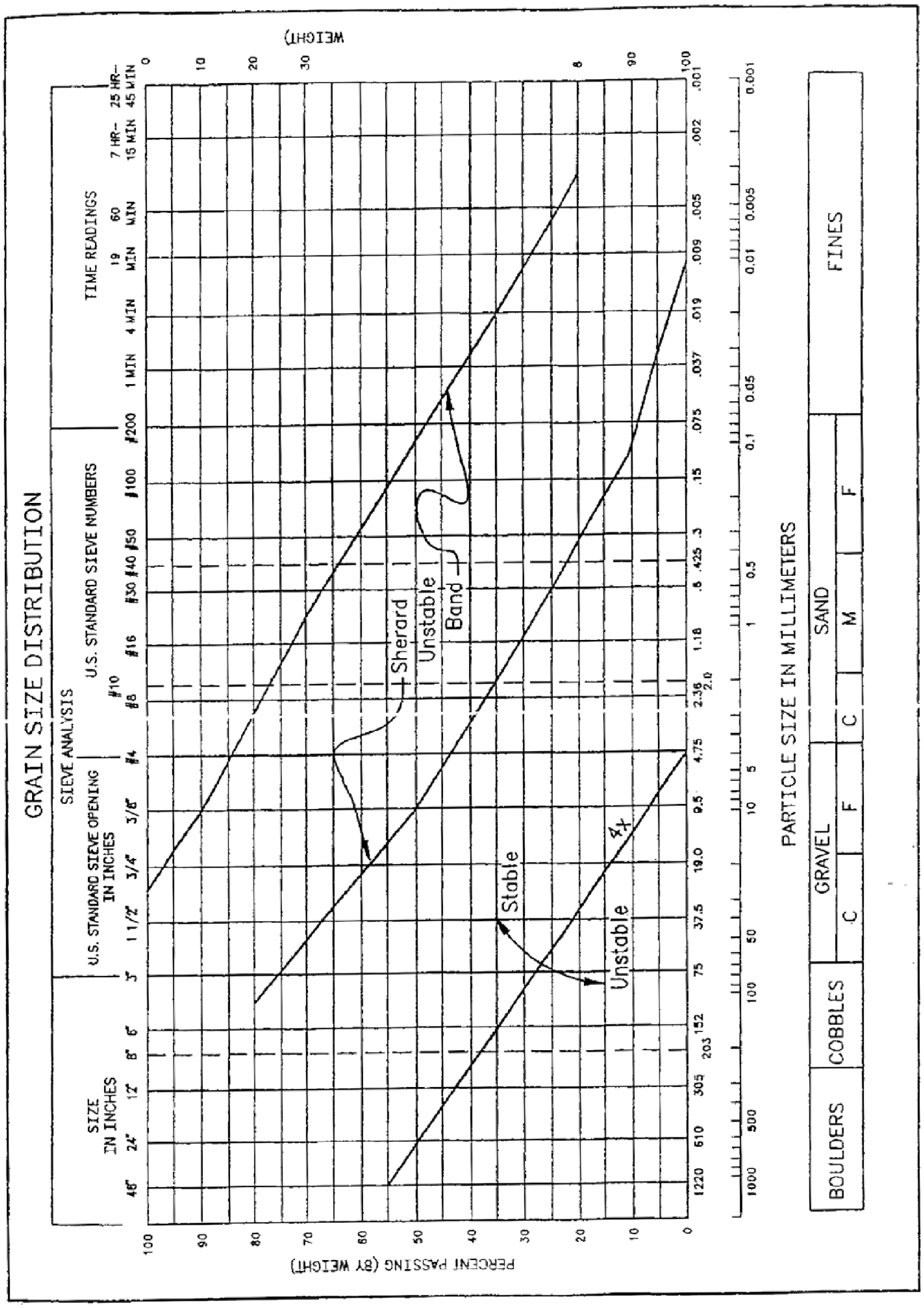

Figure 5.3.7-1. Internal instability gradation plot.

5.3.8 Dispersive Soils

For base soils with more than 15 percent fines, adequate tests should be performed to establish whether the clay fines are dispersive in character. The crumb test, ASTM D6572, and double hydrometer test, ASTM D4221, usually define this property adequately, but in some cases, pinhole, ASTM D4647, and chemical tests may also be required. Directions for sampling and testing dispersive clays is included in R-91-09, "*Characteristics and Problems of Dispersive Clay Soils*" [41].

As the name implies, dispersive clay minerals tend to "come apart" when immersed in water, as opposed to flocculation (come together), which is seen in all other types of clays. This disaggregation tends to make the individual "particles" smaller than what is measured in standard gradation testing.[15] Since the "particles" are smaller, the retention rules based on a D_{15} size do not entirely apply. For this reason, a different set of retention criteria, as described later in this chapter (see table 5.4.4-1), is used than what is used for nondispersive soils.

5.4 Gradation Selection Procedure

This section presents a step-by-step procedure for selecting the proper gradation band of a filter or drainage material. The procedure applies to zones used in embankment dams, foundation seepage collection zones such as toe drains, or any other application where seepage occurs and particle movement is to be prevented. This procedure can be used in both single- and multistage filter applications. For multistage applications, the procedure is repeated for each zone boundary (or interface) progressing from the finest to the coarsest grained soils.

Filter gradation limits achieved by this procedure will be a balance between permeability requirements on the finer side and particle retention requirements on the coarser side. The limits allow for flexibility in selection of the filter gradation band, which is dependent on the intended purpose of the material as discussed at the end of the procedure.

5.4.1 Base Soil Selection (Step 1)

5.4.1.1 Introduction

As defined in this design standard, the base soil is the soil being protected by a filter. For protective filters, the flow of water is from the base soil towards and into the filter. The base soil can be naturally occurring deposits (in situ deposits) or earthfill placed during construction. For toe drains and filter blankets, the base soils

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[15] Note that that common dispersants used in hydrometer tests (such as sodium hexametaphosphate) do not deflocculated the clay particles in the same manner as seen in the field.

are usually naturally occurring deposits since these filters are placed against natural or excavated surfaces. Chimney filters are placed against earthfill as part of original construction or existing embankment zones during embankment dam modifications.

Base soil selection is complicated by soil variability as it is represented in gradation tests. Variability will be less for embankment fill because there is blending and mixing of the source material as it is excavated from the borrow area and placed in the dam. Foundation material will have a greater degree of variability and present a greater challenge in base soil selection. Foundation soils also present a challenge in that the selection of accurate base soil gradations is only as good as the understanding of the geology. If the lithology of the subsurface deposits is poorly understood, this can lead to incorrectly grouping multiple soil gradations, resulting in a filter that is too coarse or too fine for a given geologic unit. Probably the most difficult geologic conditions to quantify are undifferentiated units. These are soil deposits that usually have limited areal extent and do not warrant mapping as unique soil layers. This may result in a broad range of soil types for consideration during base soil candidate selection.

Consideration should also be given to sampling errors, classification errors, and so called outliers. Invariably, when numerous samples are collected and obtained in earth materials, there will be one or two samples that do not appear to match all others, even when the sampled layer is thought to be homogenous. This variation can come from variability of the materials themselves or from collection or laboratory (testing) errors. When an outlier is on the finer side of the candidate gradations, a problem can arise if it is used as the representative base soil gradation because it will result in a filter being designed that is too fine.

Several case histories in the last 10 years have demonstrated the importance of not designing a filter that acts as a barrier to pervious foundation layers. This problem is especially prevalent when multiple soil categories, as described in table 5.4.3-1 (shown later, in section 5.4.3), are present. This issue can be addressed to a certain degree during base soil selection as described in greater detail in section 5.4.1.6.

Since foundation soils typically have greater variability than earthfill materials, as described above, the base soil selection procedure is different for these two classes. As would be expected, the more variable class has a longer list of characteristics that need to be evaluated (see figure 5.4.1.7-2), and the less variable material is simpler (see figure 5.4.1.7-1) (both figures shown later, in section 5.4.1.7).

5.4.1.2 Base Soil Variability

Understanding variability of the base soil is instrumental in designing adequate filter protection. While there will always be variability in base soils, typically there is greater variability in natural soil deposits than earthfill materials. Earthfill materials will have greater uniformity due to the mixing that occurs during excavation and placement operations. This is illustrated in figures 5.4.1.2-1 and 5.4.1.2-2. Figure 5.4.1.2-1 is a gradation plot of seven samples of core material from an existing dam, and figure 5.4.1.2-2 is a gradation plot of 19 samples of the foundation material for that dam. The gradations fall within a number of soil categories as described in section 5.4.3. For the core material of this example, all samples are classified as Category 2 (40 to 85 percent fines), whereas the foundation samples classify into Categories 2, 3, and 4. Since the filter design procedure is based on designing for a single category the category must be selected.

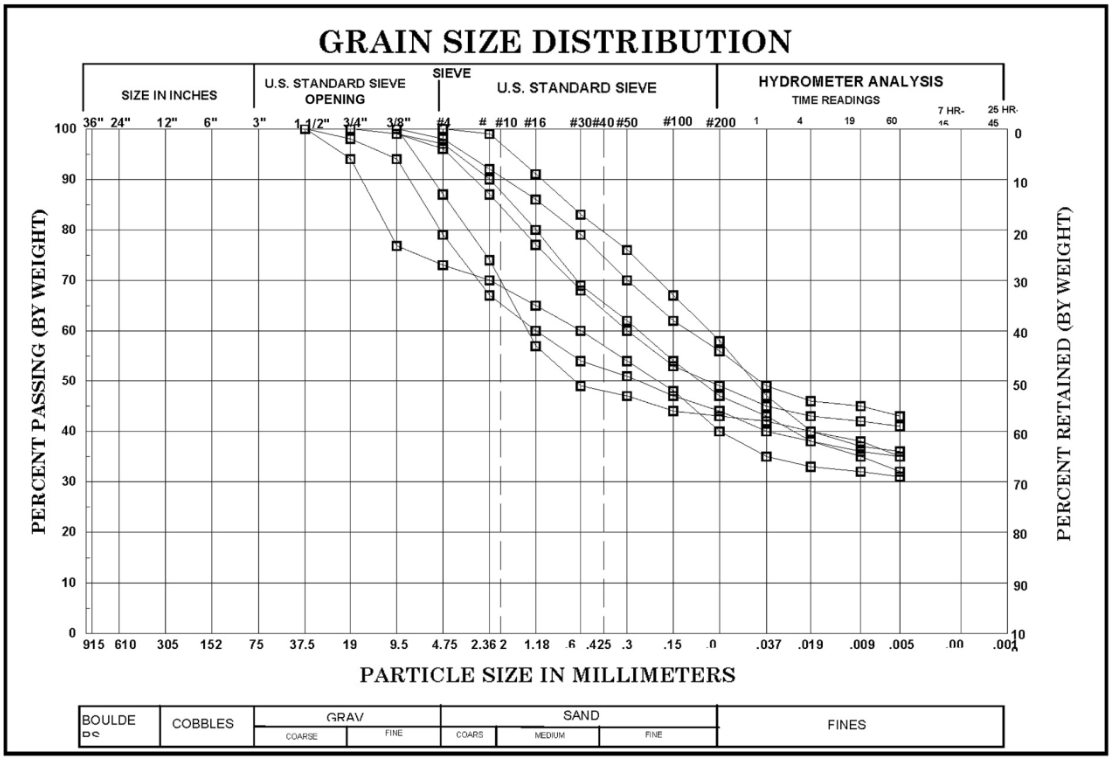

Figure 5.4.1.2-1. Gradation plot of example core material.

While the previous paragraph addressed core material found at existing dams, consideration for new construction is slightly different. Figure 5.4.1.2-3 illustrates soil gradations taken from samples obtained from a borrow area intended for use as impervious core material. Recognizing the uniformity of this borrow area, it is reasonable to use the average gradation for filter design. While using a single gradation to represent a material simplifies the filter design process, it can lead to problems that are described later. In a similar manner, the assumption that the finer side boundary of a band of gradations can act as a single conservative representation of that band can also lead to difficulties. Use of an "average" gradation to assign a base category should only take place when the borrow source exhibits uniformity and sufficient exploration has been performed to substantiate that assumption. Designing from the finer side of the band is described in more detail in section 5.4.1.7.

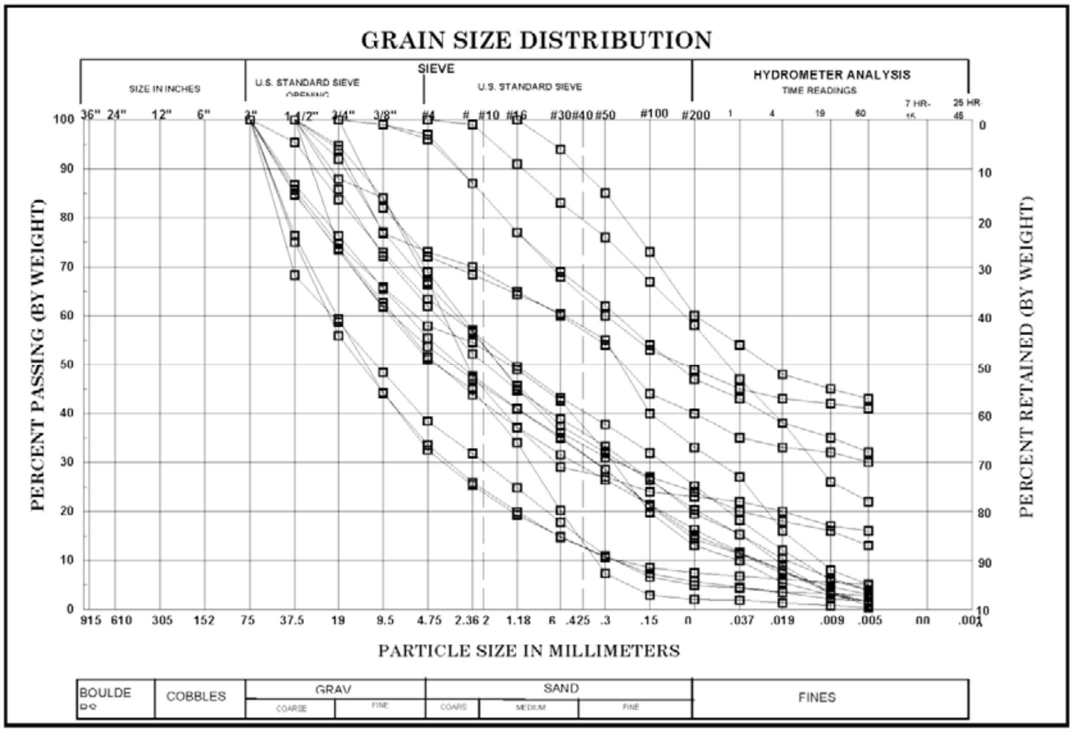

Figure 5.4.1.2-2. Gradation plot of example foundation materials.

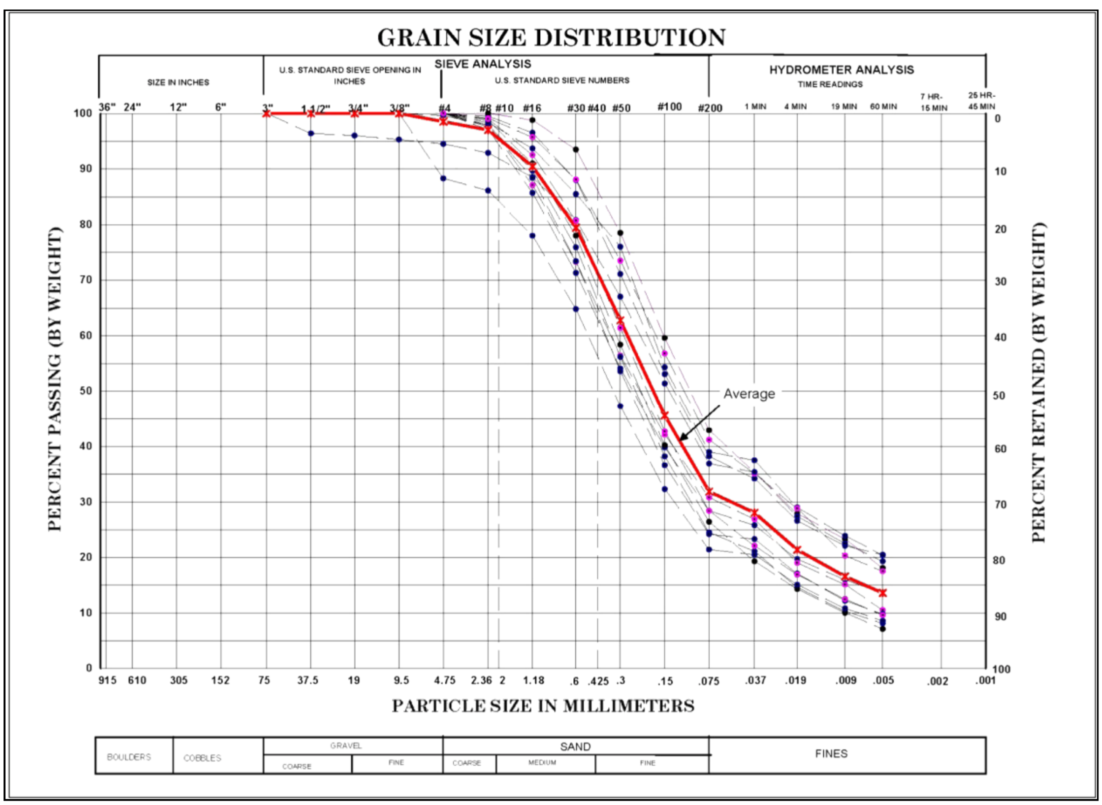

Figure 5.4.1.2-3. Gradation plot of samples taken from a potential borrow source for a core material with little variability.

5.4.1.3 Geologic Interpretation

As described in section 5.4.3, base soils are categorized according to their fines content. Subsequent design calculations are dependent on this categorization, and incorrect categorization can result in an improperly designed filter. Incorrect categorization of soils can come from:

- Incorrect geologic interpretation
- Incorrect sampling
- Grouping two or more materially different soils into one geologic unit
- Inclusion of outliers in the gradations analyzed

For naturally occurring deposits, difficulty arises in the categorization of the foundation units when the aerial extent of the units is small. Geologic categorization of foundation units is usually dependent on the geologic process that led to deposition. As an example, the foundation strata may be differentiated into "alluvium," soil deposited by swift moving water, and "aeolian," soil deposited by wind. Note that this type of categorization is not dependent on the physical properties of the soil although, typically, the physical properties almost always vary based on depositional process. In this instance, different filters can be designed for each unit when the stratigraphy is well understood. In some instances, foundations may include geologic units that are subsets of one geologic process, such as several alluvial units (alluvium 1, alluvium 2, and alluvium 3), as shown on figure 5.4.1.3-1.

Examination of the gradation indicates that the three subunits are not different, based on grain size distribution, because none of the units can be grouped together in a distinct band. Therefore, for the purpose of filter design, the three units can be grouped together into one material, alluvium, as shown in figure 5.4.1.3-2.

The converse of the previous situation can also be true—geologic classification has grouped together two soils that have different grain size distributions. Figure 5.4.1.3-3 illustrates a cross section through an alluvial fan that has been mapped as one geologic unit. Figure 5.4.1.3-4 includes the gradation plots for the 19 samples taken in an alluvial fan deposit and illustrates that two distinct groupings exist based on gradation, within the samples, Base 1 and Base 2. The Base 1 gradations are Category 2 soils, whereas the Base 2 soils are Category 3 and 4.

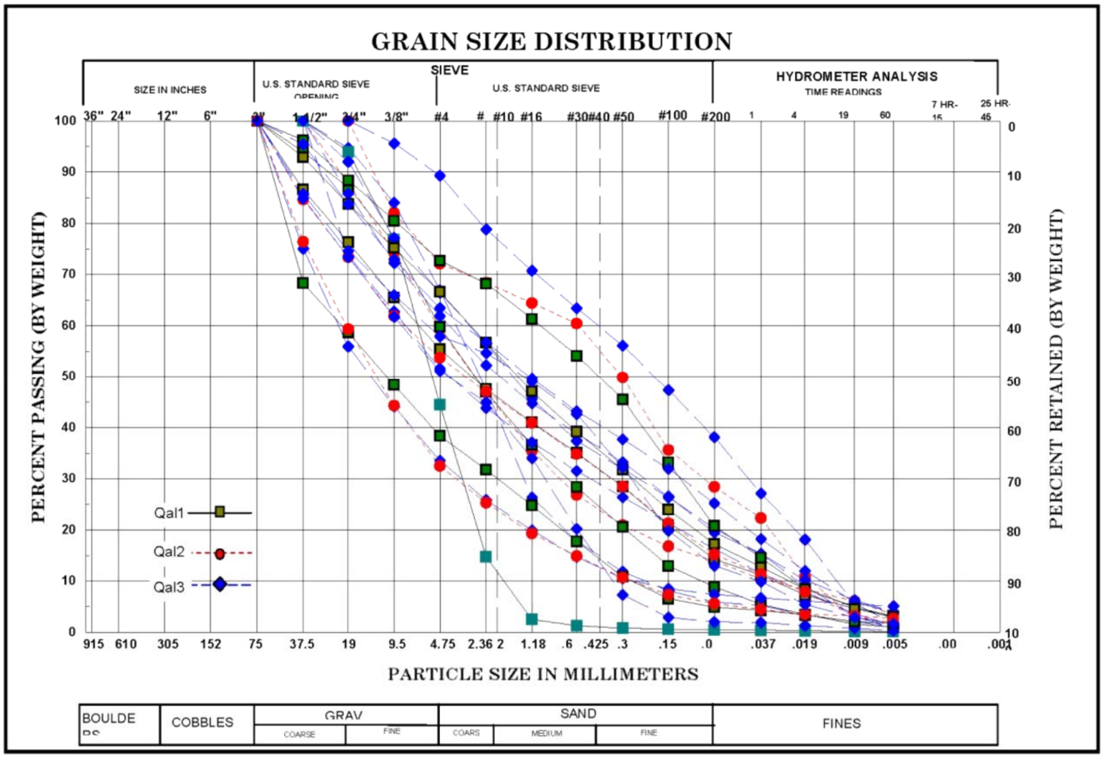

Figure 5.4.1.3-1. Gradation plots of three alluvial deposits.

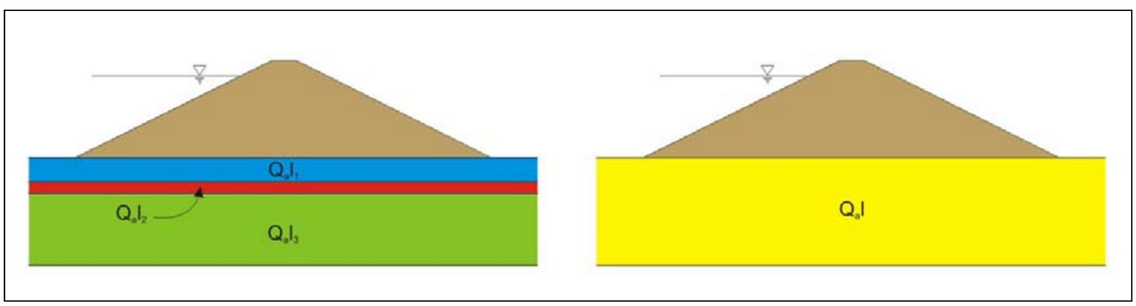

Figure 5.4.1.3-2. Geologic cross section of three alluvial deposits that is simplified to one unit due to material uniformity.

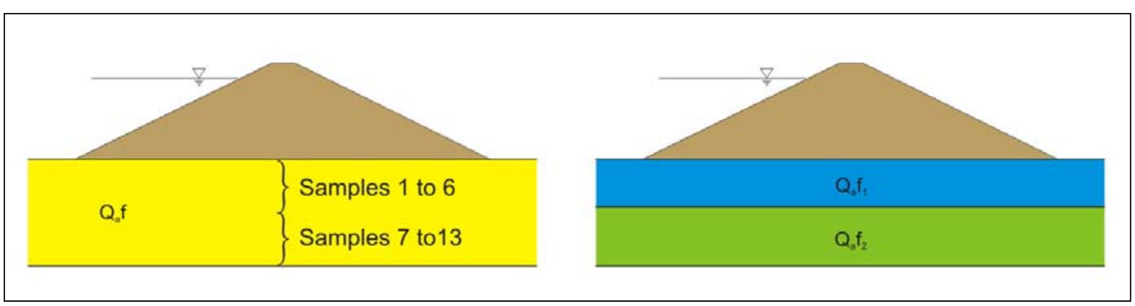

Figure 5.4.1.3-3. Geologic cross section of a single alluvial fan deposit that is separated into two distinct units due to differences in material gradation.

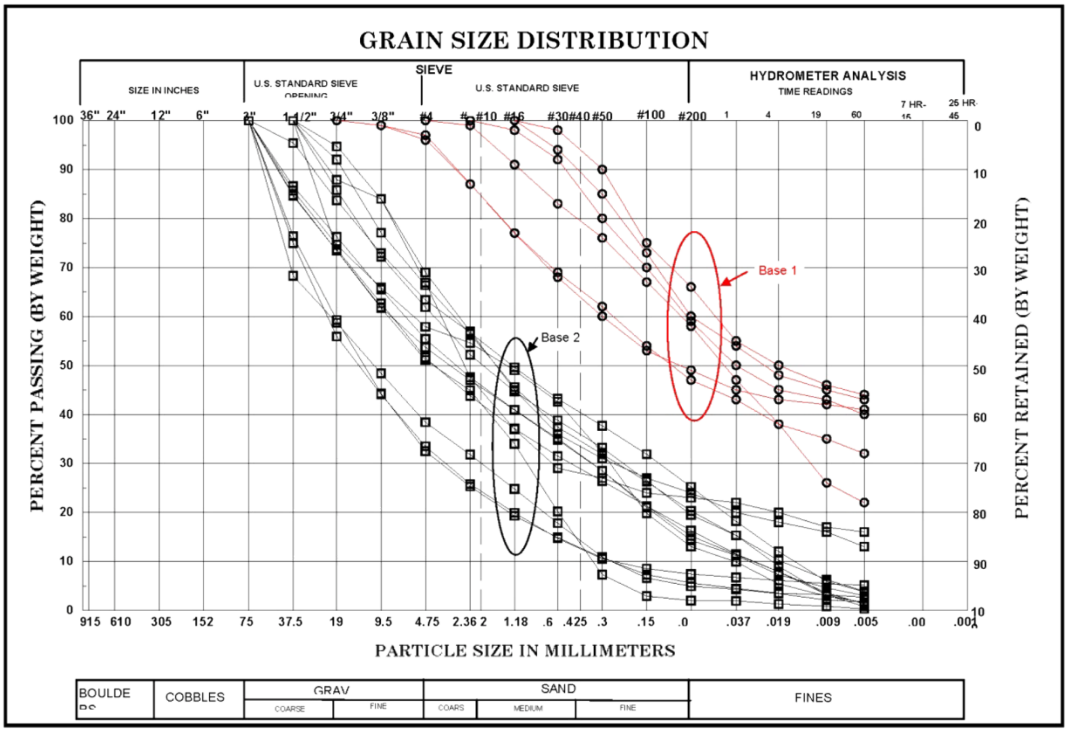

Figure 5.4.1.3-4. Gradation plot of alluvial fan material indicating two distinct units.

By going back to the drill logs, notice in the example that the six samples of Base 1 are in the upper portion of the fan, and the 13 samples of Base 2 are in the lower portion. Therefore, the alluvial fan should be separated into two subunits for filter design, Qaf1 and Qaf2. If the two bases were not separated, the filter design procedure would result in a filter gradation for the Base 1 that would likely act as a seepage barrier to the Base 2 soils. The barrier issue is described in more detail in section 5.4.1.6. Also, note that if the samples were randomly distributed through the fan, a separation could not be made.

5.4.1.4 Undifferentiated Units

Undifferentiated units are more difficult to classify for use in filter analysis. Figure 5.4.1.4-1 illustrates complex layering of silts, sands, gravels, and combinations of each. Alluvial processes can lead to these types of deposits due to the wide variety of depositional energy provided by river systems. Most erosional and depositional processes in river valleys occur during flood events. Near the river thalweg, or the deepest portion of the channel, the energy is the highest, and the largest particles are moved. Further from the thalweg, the energy is not as great, and only smaller particles are moved or the energy is so low that finer material is deposited. It cannot be assumed, though, that the present location of the thalwag will indicate the location of coarsest deposits. Since the central watercourse of a river will work its way back and forth across the valley (meander), coarser material can be found anywhere. Commonly “buried channels” or “abandoned channels” are identified during exploration and, unfortunately, sometimes during construction, when sufficient exploration is not undertaken. The sinuous nature of riverflow also complicates the erosional and depositional process. Rivers flow in a sinuous or serpentine course through their valleys. The extent of this "S" shape flow is a function of the amount of energy that needs to be shed for the given grade. Through geologic time, this serpentine path will cut across itself over and over. These are the processes that lead to the convoluted depositional sequence illustrated in figure 5.4.1.4-2.

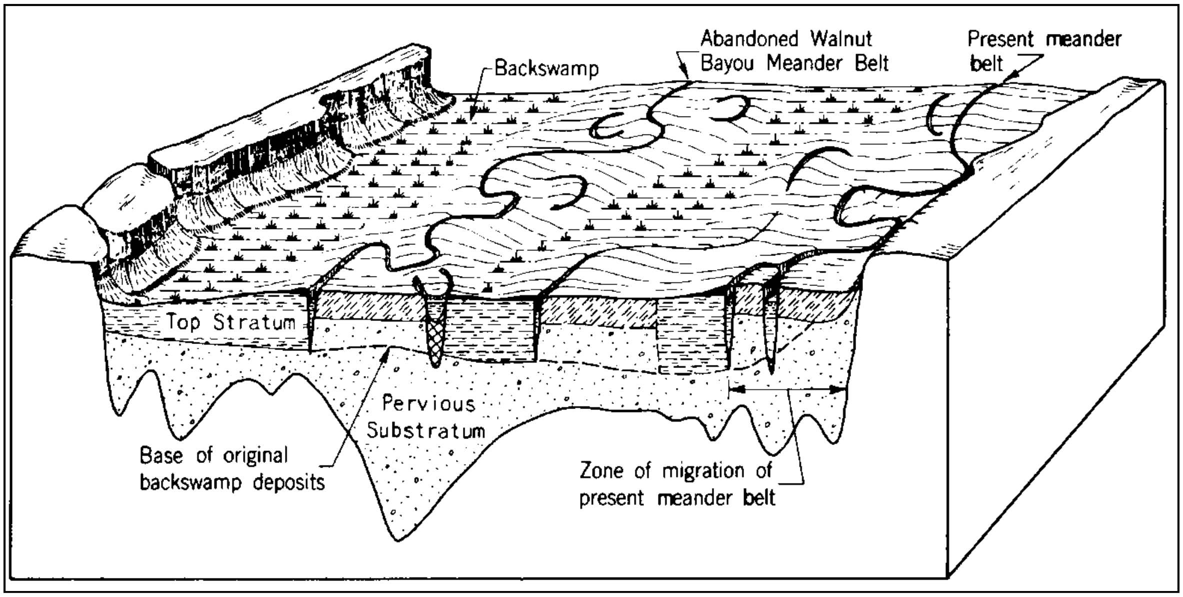

Figure 5.4.1.4-1. Meandering pattern of Mississippi River near Vicksburg, Mississippi, illustrating how a variety of materials can be deposited across a valley as the river changes course over time.

While the previous example describes the method by which widely varying deposits can occur in alluvium, similar deposits are also seen from glacial and alluvial fan processes.

It should be noted that extent and continuity are difficult to ascertain for undifferentiated deposits. One may conclude from drawing a simple upstream to downstream cross section that a unit of particular interest is not continuous since it is truncated by other materials. Consider the case where a gravel deposit is identified but the cross section shows that it is truncated by silts and sands as shown in figure 5.4.1.4-2. Since the gravel layer may actually have a serpentine alignment, it would be incorrect to assume it is truncated as shown in the cross section.

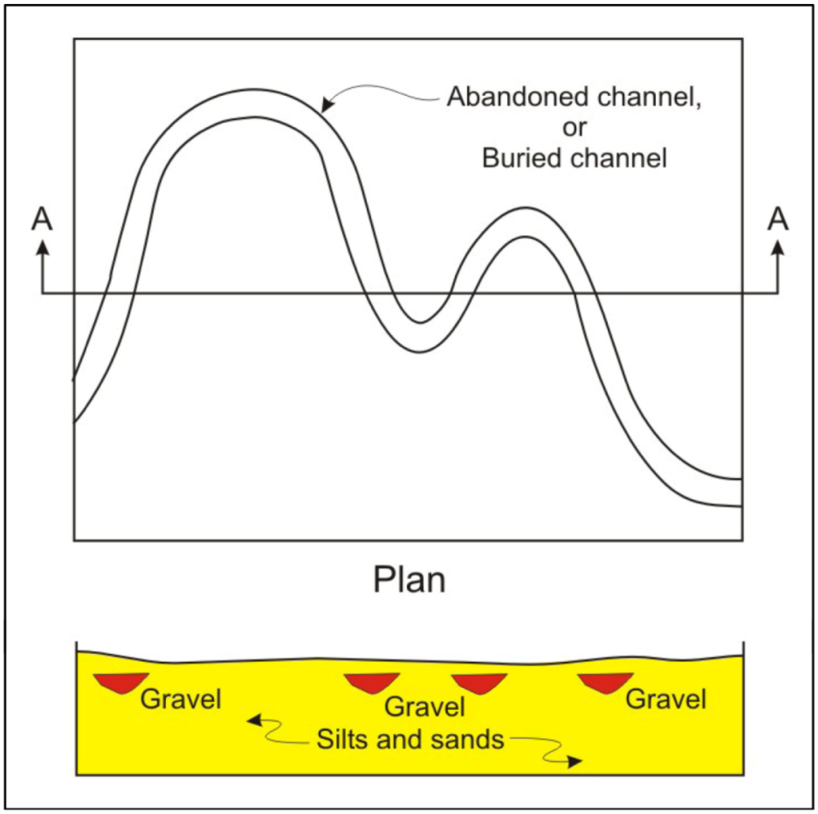

Figure 5.4.1.4-2. Plan and sectional view of a meander illustrating so-called gravel lenses.

5.4.1.5 Outliers and Sampling Errors

Gradation test data may include statistical results that are not representative of in situ conditions. This is illustrated in the gradation plot of figure 5.4.1.5-1. Here, a single sample is more fine grained than the seven other samples that all fall within the same gradation range. A number of factors could lead to this one sample being different from the other seven:

1. Incorrect sampling method (i.e., technician did not include larger test pit material because it would not fit in the bag or was too heavy). See section 5.6.2.1 for correct sampling procedures.

2. Gradation test was performed incorrectly.

3. Inventory error (i.e., sample is actually from another location).

4. Sample was taken from near the ground surface (topsoil), which will be removed during construction (stripping).

5. A very thin layer exists.

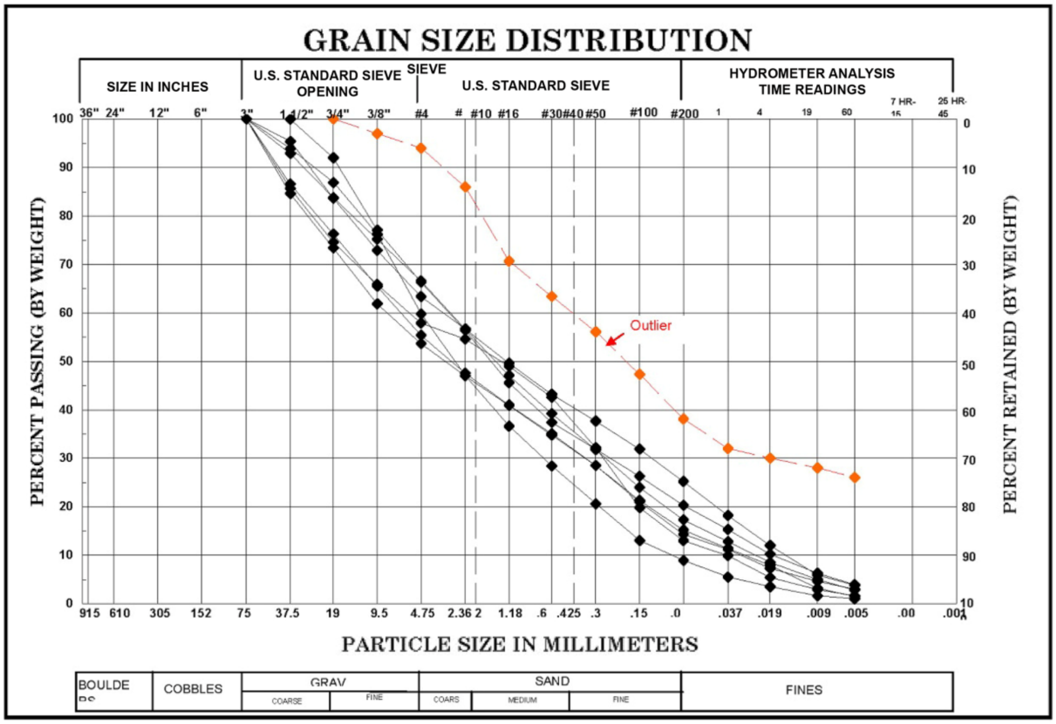

Figure 5.4.1.5-1. Gradation test samples including an outlier.

The designer should investigate these factors to ensure that the sample is valid for inclusion in the data set. If an error is found, it should be corrected so that accurate information is included in the data set. It is difficult to provide rules for exclusion of outliers, but they are generally identified visually as illustrated in figure 5.4.1.5-1. Eliminated outliers should not be greater than 15 percent of the sample set. If it is thought that greater than 15 percent of the sample set are outliers, the geologic interpretation, as described in the previous sections, should be revisited.

Another error that can arise in categorizing soils is related to sampling errors. One of the most common errors in this regard is the use of undersized samplers. The commonly used split spoon sampler has an inside opening size of 1-7/8 inches, indicating that it is unable to sample coarse gravel and cobbles. Omission of these grain sizes can lead to incorrect base soil categorization and filter design, even with regrading. Similar errors can occur with other, larger size samplers. The designer should always check that the correct size sampler is used for the expected exploration conditions. As described in section 5.7, the use of test pits is the preferred exploration method for evaluation of base soils. Collecting bag samples of materials obtained from these pits provides the most accurate base soil data, as well as an indication of stratigraphy (layer) information that may not be detected from drillhole data.

Caution should also be exercised to not utilize sample data that is distant from the filter location. As an example, consider an exploration program executed across a site in which samples are taken every 10 feet. In some drillholes, the first sample at the ground surface could not be retrieved. Samples from the successful 10-foot depth, as well as 20- and 30-foot depths, were tested and used to represent the foundation soil (base soil). The construction of a 6-foot-deep toe drain is planned at the site using these data. It should be recognized that this exploration program did not address the upper 10 feet of the foundation, and that layer could be materially different than what is seen lower. Therefore, this base soil could be misleading and result in an incorrectly designed filter for the toe drain.

5.4.1.6 Filter Barriers

Using filter design procedures, it is possible to design a filter that is less permeable than portions of the foundation. Such a barrier is illustrated in figure 5.4.1.6-1. The figure represents a lenticular foundation of undifferentiated soil deposits. While no distinct layer of gravel is present, concentrated seepage can occur through the more pervious lenses. As shown in the figure, a sand filter will then act as a barrier at the bottom of the trench. This can result in less than expected flow quantity entering the pipe and higher pressures.

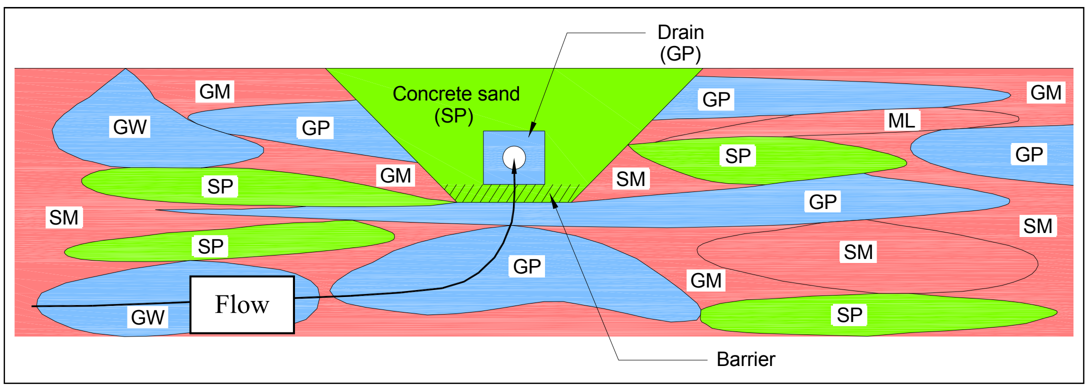

Figure 5.4.1.6-1. A filter for a toe drain that is acting as a barrier to a more pervious foundation layer.

Figure 5.4.1.6-2 is a second method of visualizing this issue. This figure summarizes the base soil gradations, as well as a proposed filter. The base soil is shown by the limits of the regraded curves of the foundation soil samples. The regrading consists of scalping (mathematically) the material larger than the No. 4 sieve as described in filter design procedures. Also shown on the plot is the average gradation for concrete sand, a common filter material. The hatched portion of the graph indicates the range of base soil gradations that would be coarser than the filter. Since this filter would be finer than these base soil gradations, it would act as a barrier to those materials (about 25 percent of the total base soil range taken at the D_{15} size).

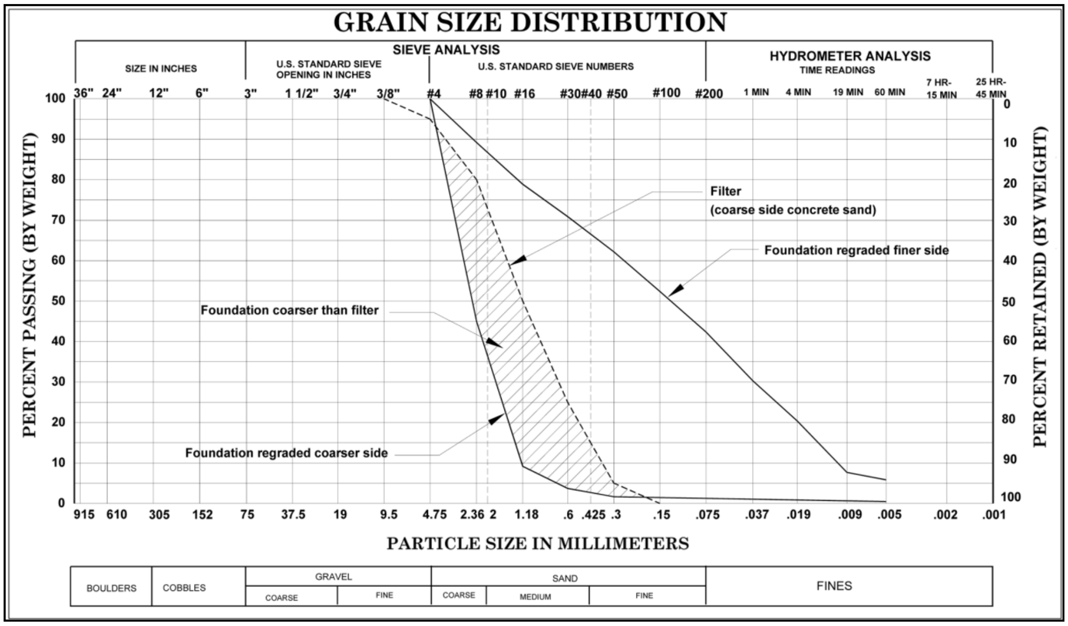

Figure 5.4.1.6-2. The filter barrier concept illustrated on a grain size distribution plot.

As a final example, figure 5.4.1.6-3 illustrates the effect of a filter barrier on theoretical soil deposits. The upper portion of the figure shows a box consisting of three layers of soil, each 1 foot thick. A head is applied to the left side of the box and drain on the right side. The configuration results in a head drop of 10 feet across the box. The box is 100 feet long, as is the flow length. Utilizing Darcy's equation, total flow through the box is calculated as indicated in the figure. The resultant total flow for this arrangement is 5×10^{-1} cubic feet per minute (ft^3/min).

Taking the same arrangement and adding a filter barrier, shown on the right side of the box in the lower half of the figure, results in a total flow of 9.8×10^{-3} ft^3/min, 1/50th of the original flow.

Note that when it is thought that a filter may impede the flow of a more pervious foundation layer, a second stage can be used to increase drainage efficiency.

5.4.1.7 Representative Base Soil Selection Procedure

Since the filter design procedure is based on the use of a single gradation, a procedure is required to transition from multiple base soil gradations. The process is further complicated if the base soil can be classified within two or more categories. Due to the large variability of base soil gradations that may be encountered in practice, engineering judgment is required for each situation. Consideration is also needed for the specific application of the design element as well as the failure mode that is being addressed. As an example this section will describe a procedure that addresses the issues discussed in the four preceding sections. Since considerations for earthfill and in situ soils are different, two procedures are used. The selection process for earthfill is shown in figure 5.4.1.7-1, and the process for in situ (foundation) soils is shown in figure 5.4.1.7-2.

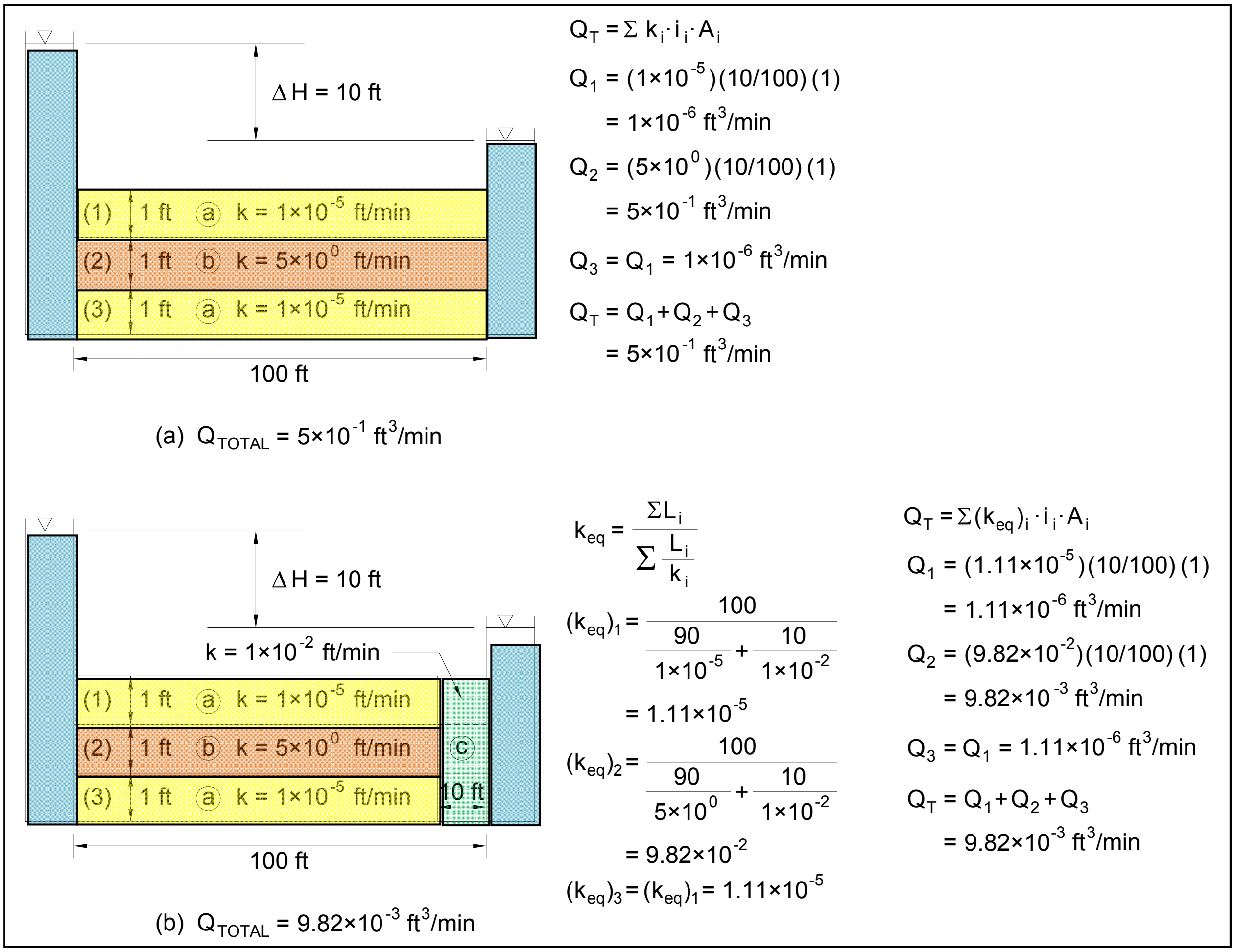

Figure 5.4.1.6-3. The filter barrier concept illustrated as flow through a laboratory box.

As illustrated on figure 5.4.1.7-1,[16] the first step in base soil categorization is to determine if the dam is new or existing. For new dams, if the base soil falls within one category, then the average gradation of the base soil samples is generally used. If the base soils fall within more than one category for new or existing dams, then generally use the finer side of the range of gradations. **Note**: the finer side of a range of gradations is illustrated in figure 5.4.1.7-3.

If the earthfill falls within more than one category and it is not a drainage feature (toe drain, relief well, etc.), it too can be based on the finer side of the range of gradations. If an earthfill base is placed into more than one category, and the filter needs to act as a drainage feature, use the finer side of the highest number category.

[16] Filter design in this flowchart is controlled by particle retention criteria.

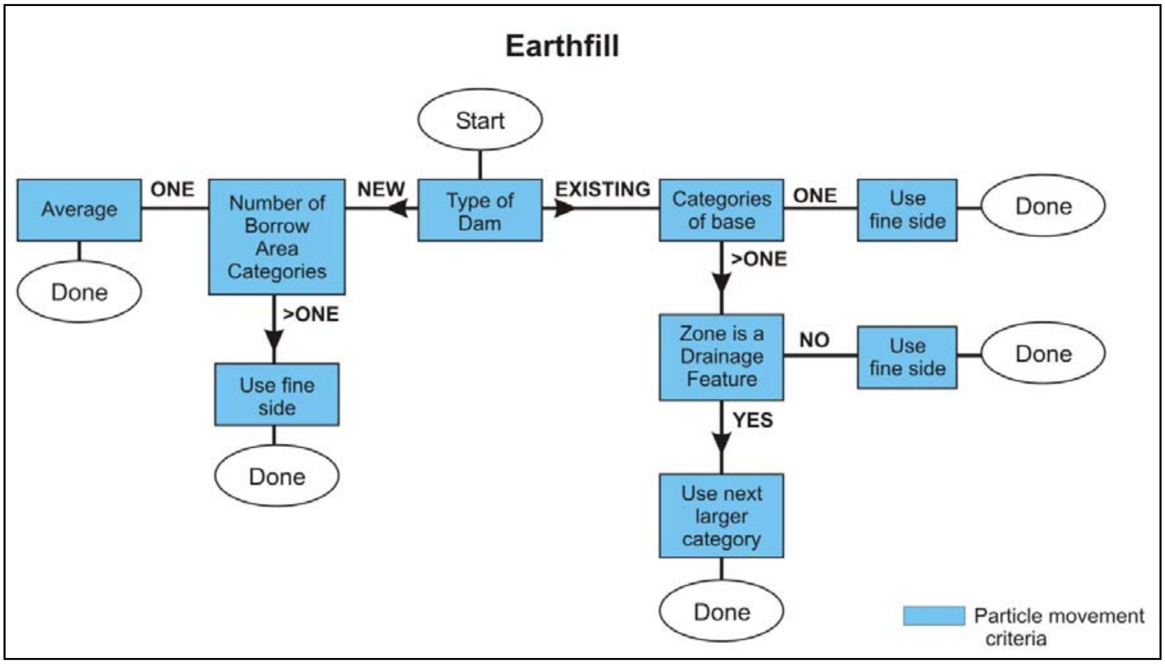

Figure 5.4.1.7-1. Base soil selection flowchart for earthfill.

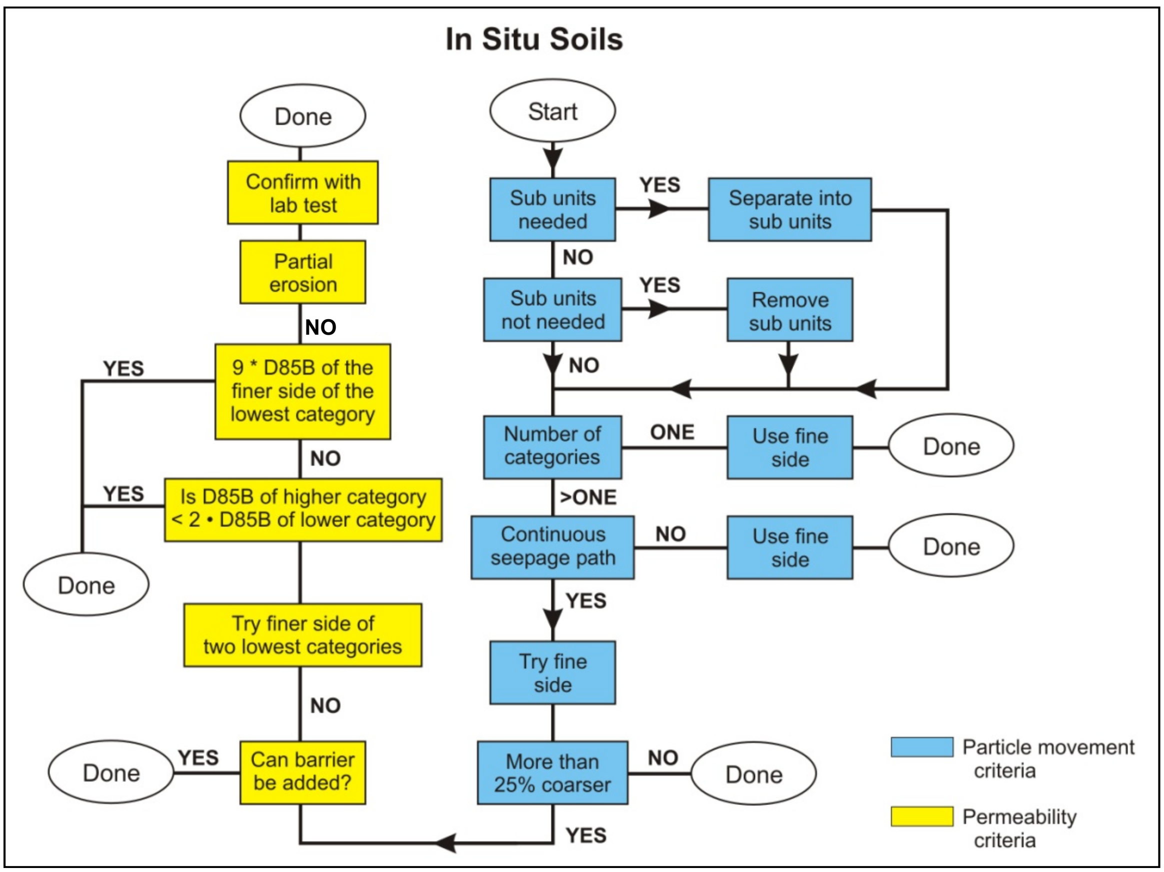

Figure 5.4.1.7-2. Selection process for in situ base soils.

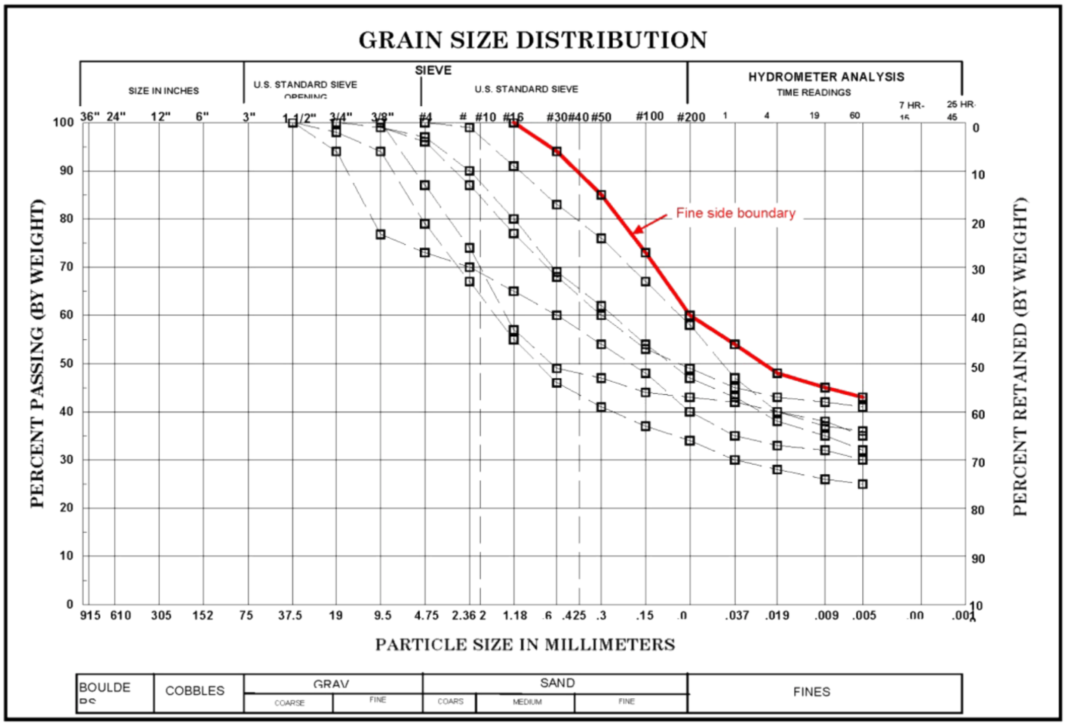

Figure 5.4.1.7-3. Example of finer side of a range of soil gradations.

Base soil selection for in situ soils is more complicated due to the greater variability of natural soil deposits than earthfill. This selection process does not differentiate between existing and new dams since it is not germane. In evaluating filters for complex foundation soil deposits, designers must carefully consider potential seepage pathways and the type of internal erosion mechanism that needs mitigation. Figure 5.4.1.7-2 presents a potential means of approaching this type of evaluation. Using figure 5.4.1.7-2,[17] the first steps are to check whether the in situ materials are categorized correctly based on grain size distribution as described in section 5.4.1.2. After this is complete, determine how many categories the range of base soils fall within. If only one category is present, select the fine side of that category. If more than one is present, determine if a continuous seepage path is present, as described in the section 5.4.1.2. If the seepage path is not continuous, use the finer side of the lowest number category. If a continuous seepage path is present, perform a trial design using the fine side of the lowest numbered category. Check if the finer side of the trial filter gradation is finer than 25 percent of the base soil gradations. If no more than 25 percent of the base soils are coarser than the fine side of the trial filter, the trial is acceptable. If more than 25 percent of the base soil gradations are coarser than the fine side of the filter, the overall project design should be evaluated. Design elements that reduce the volume of seepage that should be considered for this situation are cutoff walls, upstream blankets, and grouting.

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[17] Filter design in this flowchart is controlled by particle retention criteria for some cases and permeability for other cases. The different cases are described in the narrative.

If the design elements cannot be addressed, site conditions are exceptionally poor (usually at existing dams), or costs are prohibitive, then the design proceeds by emphasizing permeability requirements instead of particle retention requirements. This is accomplished by comparing the trial filter design based on the finer side of the two lowest numbered categories. If the $D_{85}B$ of the higher numbered category is less than twice the $D_{85}B$ of the lower numbered category, the design based on the higher numbered category is acceptable. Note that this design eliminates the factor of safety against particle movement that is implicit in all designs that meet particle retention criteria.

If the $D_{85}B$ of the higher numbered category soil is more than twice the $D_{85}B$ of the lower numbered category, perform a new trial. In that trial, find the $D_{15}F$ of the filter by multiplying the $D_{85}B$ of the finer side of the lowered numbered category by 9. That is:

$$D_{15}F = 9 * D_{85}B$$

This will result in a filter that will allow partial, but not continuous, erosion. This design should always be confirmed by a laboratory filter test using the **lowest category soil** and the proposed filter material.

5.4.2 Regrading Base Soil (Steps 2 and 3)

Regrading of the base soil at the beginning of the procedure is a critical step that must be followed, when applicable[18], in order to obtain a correctly designed filter. The concept of regrading was developed by Sherard to correct for broadly graded soils. These soils, as explained in section 5.3.8, can be internally unstable, and regrading corrects for this phenomenon. Permitting the inclusion of gravel (+ No. 4 sizes) within a base soil gradation will lead to a large $D_{85}B$ size and, subsequently, a large $D_{15}F$ size. Since gravel particles do not have any particle retention capability in broadly graded or gap-graded soils, the resulting filter will be too coarse to provide particle retention of the finer fraction of the base soil (i.e., the filter will not meet particle retention criteria for the base soil).

This problem is illustrated graphically on figures 5.4.2-1 and 5.4.2-2. Figure 5.4.2-1 shows a base soil that has not been regraded. The original gradation shows that the fraction of the soil larger than 3/8 inch is internally unstable. That is, it is flatter than the shown stability line (also see figure 5.3.8-1, shown earlier in section 5.3.8) for the stability line). Sizing a filter for this material results in a filter consisting primarily of coarse gravel, as shown on figure 5.4.2-1. This design results in the silt and fine sand of the base material eroding through the voids in the coarse gravel filter.

[18] The exceptions are described later in figure 5.4.2-3. These exceptions basically relate to uniform gravels and they apply when designing coarser second stage zones, such as drain envelopes.

Figure 5.4.2-2 shows the same base soil but regraded on the No. 4 sieve. Notice that this regraded soil is internally stable (coarser fraction steeper than the stability line). The filter design based on the regraded soil is a fine gravel with 10 percent sand. This design will not permit movement of the silt and fine sand of the base soil through the sand and fine gravel filter.

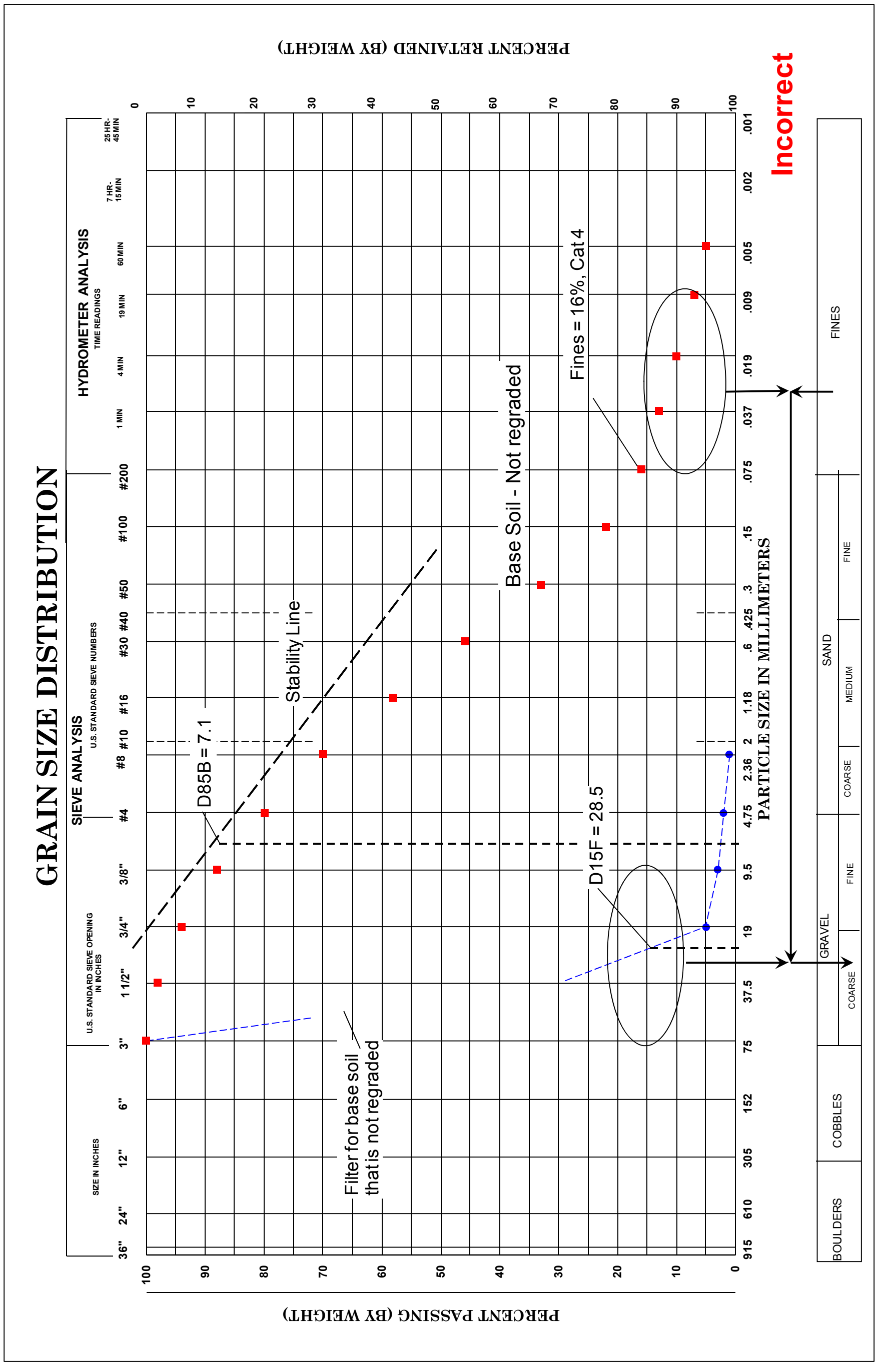

Figure 5.4.2-1. Example of an incorrectly designed filter because the base soil was not regraded.

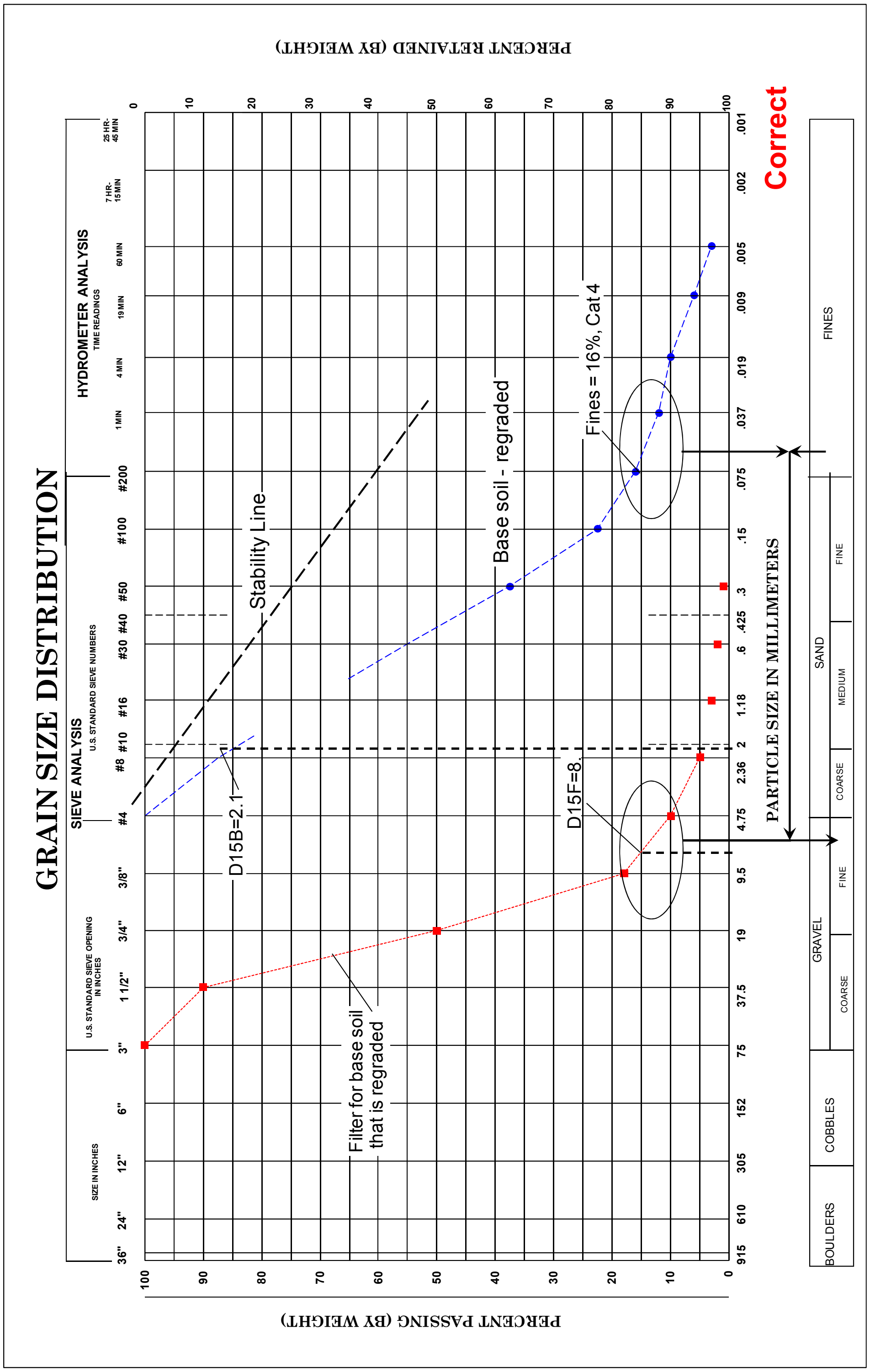

Figure 5.4.2-2. Example of the same material as shown in figure 5.4.2-1.

Since regrading effectively removes material larger than the No. 4 sieve, it does not apply to all soils, especially uniformly graded gravels which, by definition, are larger than the No. 4 sieve. Figure 5.4.2-3 is used to determine which base soils require regrading and the operation used to achieve the regrading. As shown in the figure, when a soil does not contain any gravel (particle larger than the No. 4 sieve), regrading is not required (step 2a). If the soil does contain gravel, it still may not require regrading if it meets all of the three properties listed in the figure (step 2b). If one or more of the properties are met, the soil should be regraded using the procedure described in step 3.

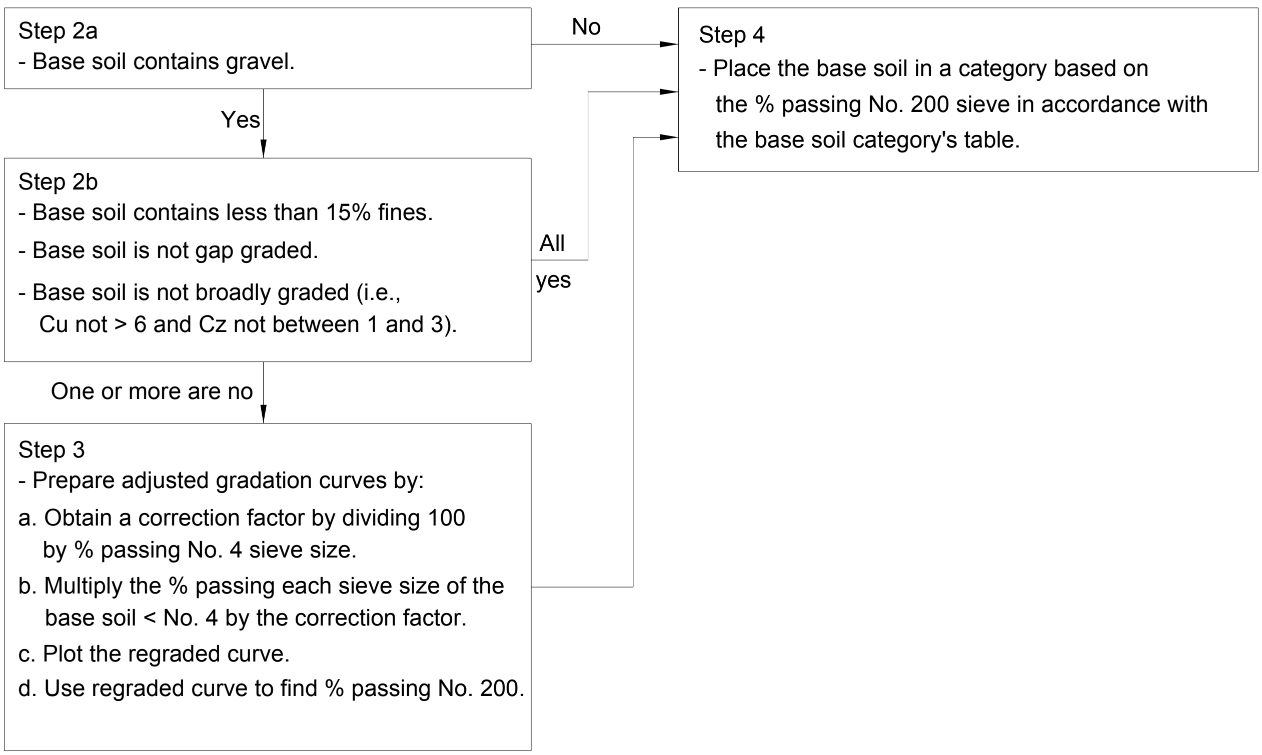

Figure 5.4.2-3. Logic diagram showing when regrading of the base soil is required.

An example of the calculation used in step 3 is shown in figure 5.4.2-4.

Sieve Size	Original Percent Passing	Adjustment	Final Percent Passing
3"	100.0		
1 1/2"	85.7		
3/4"	74.6		
3/8"	65.9		
#4	57.9	(57.9 / 57.9) x 100	100.0
#8	54.6	(54.6 / 57.9) x 100	94.3
#16	49.0	(49.0 / 57.9) x 100	84.6
#30	42.6	(42.6 / 57.9) x 100	73.6
#50	32.2	(32.2 / 57.9) x 100	55.6
#100	19.8	(19.8 / 57.9) x 100	34.2
#200	13.0	(13.0 / 57.9) x 100	22.5
1 min	9.9	(9.9 / 57.9) x 100	17.1
4 min	5.4	(5.4 / 57.9) x 100	9.3
19 min	2.9	(2.9 / 57.9) x 100	5.0
60 min	1.6	(1.6 / 57.9) x 100	2.8

Typ.

Figure 5.4.2-4. Example regrading calculation.

5.4.3 Base Soil Categories (Step 4)

Different soils have differing abilities to erode from water flowing through them. A nondispersive plastic clay will be more resistant to erosion than nonplastic silts due to the chemical bonds between the clay particles. Gravels will be more resistant to erosion than fine sands due to their greater individual particle weight and the tractive force required to move a particle. For this reason, soils are classified into categories based on fines content (percent finer than the No. 200 sieve). The next step in the procedure is to classify the base soil gradation into one of four categories in accordance with table 5.4.3-1.

Table 5.4.3-1. Base soil categories

Base soil category	Percent finer than No. 200 sieve (0.075 mm) (after regrading where applicable)	Base soil description
1	> 85	Fine silts and clays
2	40 – 85	Silts, clays, silty sands, and clayey sands
3	15 – 39	Silty and clayey sands and gravels
4	< 15	Sands and gravels

Note: mm = millimeter

5.4.4 Particle Retention Requirement (Step 5)

To satisfy particle retention requirements, determine the maximum allowable $D_{15}F$ size in accordance with table 5.4.4-1. Selection is based on the $D_{85}B$ of the regraded, if applicable, base soil. Plot this as **Point A** (see figure 5.4.4-1 for an example). Note that dispersive soils are specifically addressed in this step.

Table 5.4.4-1. Filtering criteria

Base soil category	Filtering – Maximum D15F
1	The maximum $D_{15}F$ should be ≤ 9 x $D_{85}B$, but not less than 0.2 mm, unless the soils are dispersive. Dispersive soils require a maximum $D_{15}F$ that is ≤ 6.5 x $D_{85}B$ size, but not less than 0.2 mm.
2	The maximum $D_{15}F$ should be ≤ 0.7 mm unless soil is dispersive, in which case the maximum $D_{15}F$ should be < 0.5 mm.
3	A. For nondispersive soils, the maximum $D_{15}F$ should be: $\leq \left[\frac{40-A}{25}\right]\left[\left(4xD_{85}B\right)-0.7mm\right]$ **+ 0.7mm** where: A = Percent passing No. 200 sieve. When 4 x $D_{85}B$ is less than 0.7 mm, use 0.7 mm B. For dispersive soils, use 0.5 mm.
4	The maximum $D_{15}F$ should be ≤ 4 x $D_{85}B$ of base soil after regrading.

5.4.5 Permeability Requirement (Step 6)

To satisfy permeability requirements, determine the minimum allowable $D_{15}F$:

$$D_{15}F \geq 5 \text{ x } D_{15}B\text{, but not less than 0.1 mm}$$

Plot this as **Point B** (see figure 5.4.4-1 for an example).

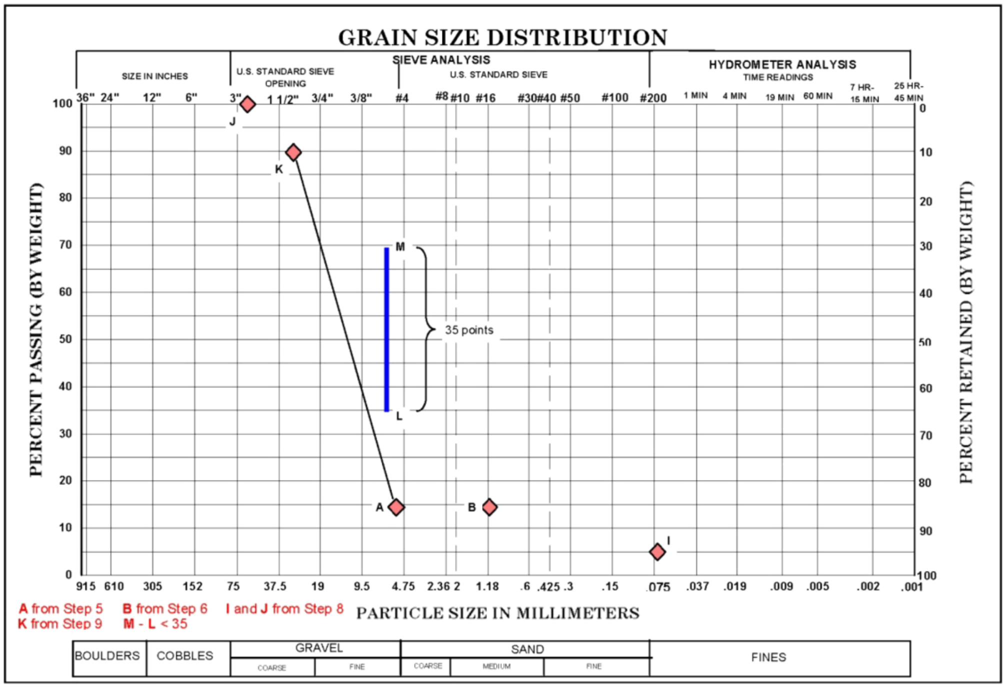

Figure 5.4.4-1. Example gradation limits to address gap-graded materials.

5.4.6 Fines Content and Oversize Limits (Step 7)

To limit the amount of fines and oversized material for first stage filters, limits are placed on the minimum D_5F and maximum $D_{100}F$ according to table 5.4.6-1:

Table 5.4.6-1. Maximum and minimum particle size criteria

Base soil category	Maximum $D_{100}F$	Minimum D_5F
ALL categories	≤ 2 inches (51 mm)	0.075 mm (No. 200 sieve)

The D_5F limit is indicated by **Point I** and $D_{100}F$ by **Point J** on figure 5.4.4-1.

To limit segregation potential, determine $D_{90}F$ from table 5.4.6-2.

Table 5.4.6-2. Segregation criteria

Base soil category	If $D_{10}F$ is: (mm)	Then, maximum $D_{90}F$ is: (mm)
ALL categories	< 0.5 0.5–1.0 1.0–2.0 2.0–5.0 5.0–10 > 10	20 25 30 40 50 60

The $D_{90}F$ limit is represented by **Point K** on figure 5.4.4-1.

Note that the limit for maximum particle size given in table 5.4.6-1 (≤ 2 inches) is intended for first stage, or 'sand' filters. Coarser second stage filters, such as drain envelopes, may include particles larger than 2 inches. Additionally, the limitation of fines content (Minimum D_5F) is measured in-place. Measurement in a stockpile will need to be less (2 percent) to account for breakdown during placement and compaction.

5.4.7 Prevention of Gap Grading (Step 8)

If the specified gradation limits are too wide, it is possible that a filter can be produced that is gap graded. To limit this potential, additional constraints are introduced in this step. This is done by limiting the difference of the lower limit of percent passing and the upper limit of percent passing to no more than 35 percentage points. This is shown graphically in figure 5.4.4-1 as the **LM bar**, which has a maximum length of 35 percentage points. The bar can be moved around the gradation plot, but **Point L** cannot move to the left of a line drawn between **Points A and K** and cannot move any further to the right than **Point B**. As described in the next step, the **LM bar** can be moved around to a location compliant with the intended use of the filter. For finer grained filters intended to focus on particle retention, the bar would be positioned to the right. Coarser filters focusing on permeability would be positioned to the left.

5.4.8 Final Gradation Selection (Step 9)

Using the previous steps, minimum and maximum limits (control points) for grain size distribution are found. The seven control points are labeled **A, B, I, J, K, L**, and **M** as shown on figure 5.4.8-1. These limits allow flexibility in the last step of filter gradation selection based on the intended purpose of the filter. This section will describe how to select a gradation band within these limits for filters in different applications. For purposes of this example, the base soil is assumed to be the same for each of these applications. The examples are based on a Category 2 base soil.

The limits for this example Category 2 material are shown in figure 5.4.8-1. These limits can be thought of as the range in which filter gradation candidates can be entered. Filter gradation candidates within these limits will meet criteria for permeability (minimum limit) and particle retention (maximum limit). Depending on the planned use for a candidate, the gradation can be anywhere within this range and still meet these criteria. The next sections present several examples. **These gradations are presented as examples and should not be used for the applications described without going through the entire design procedure described previously.**

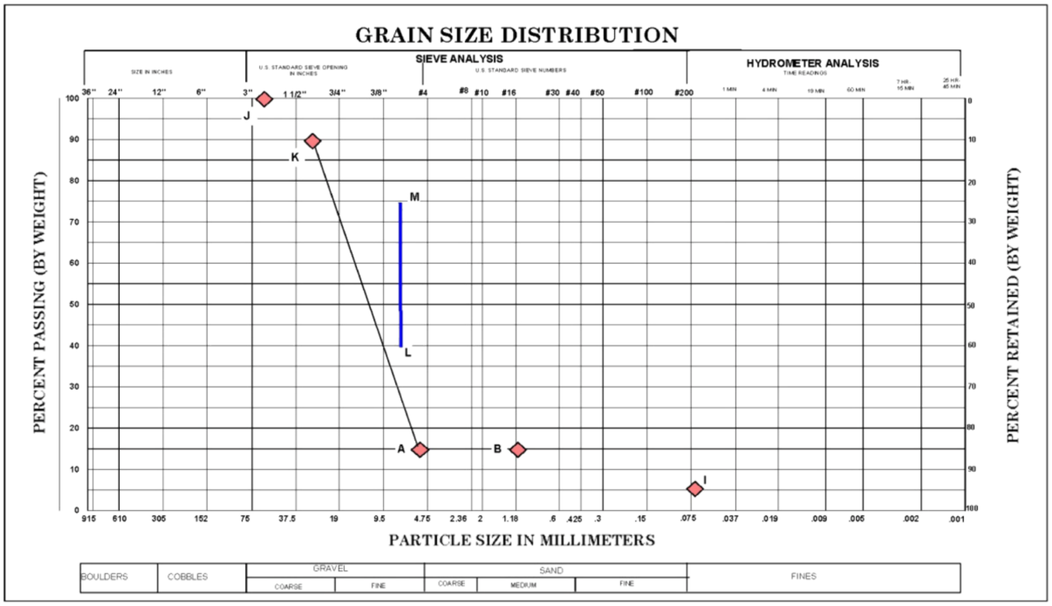

Figure 5.4.8-1. Limits (control points) for an example Category 2 base soil.

In general, the method of selecting the gradation band inside the limits can be done in three steps:

1. Begin with the smaller grain sizes because this is where the particle retention and permeability constraints are located (**Points A, B**, and **I**). If particle retention is the more critical criterion, the gradation should be set closer to **Point B**. If the permeability criteria are more important, the gradation band should be closer to **Point A**.

2. Locate **Bar LM** based on the amount of uniformity that is desired in the gradation. If a more uniform gradation is desired, move the bar to the right, near **Point B**. If a broader gradation is desired, move the bar to the left, near the **AK Line**.

3. Select the gradation range for the largest grain sizes. This portion of the gradation band has the least amount of constraints on it (only **Points J and K**) and offers the most flexibility in the gradation selection. In general, the gradation bands should have the same or slightly flatter slopes than what is seen in the range of 30 to 60 passing. The gradation should also curve to the left similar to the relationship seen between **Points J and K**.

5.4.8.1 Particle Retention Filter

In situations where particle retention is of the greatest interest, a filter gradation shown in figure 5.4.8.1-1 can be used. This filter gradation could be used for a chimney filter in which protection of the core is the primary concern. It could also be used for toe drains when large amounts of seepage are not expected. Notice that this filter gradation is intentionally uniformly graded to minimize segregation potential.

The gradation was set by first selecting the finer side of the gradation band near **Point B**. Next, since a more uniform gradation is desired, **Bar LM** is set to the right, near **Point B**. The gradation is extended to pass through the **Bar LM** and finished by decreasing the slope and curving the gradation for the coarsest portion of the gradation. The resulting filter is a fine to medium sand.

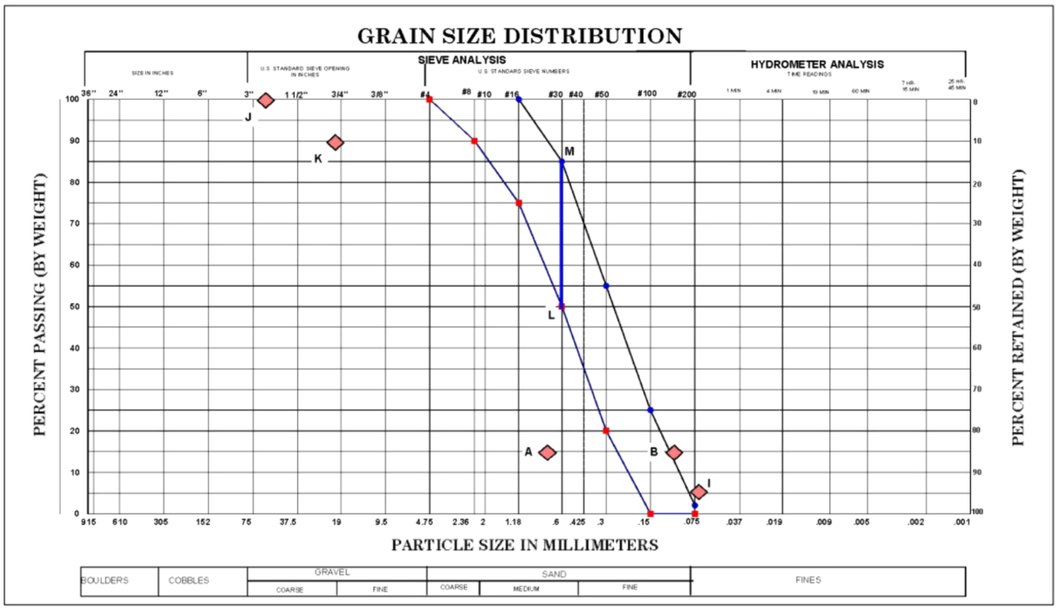

Figure 5.4.8.1-1. Example particle retention filter gradation.

5.4.8.2 Drainage Filter

For cases in which drainage is the primary goal, such as toe drains on pervious foundations, the filter gradation shown on figure 5.4.8.2-1 can be used. In this example the D_{15} gradation is set near the upper limit of particle size (Point A) to maximize the permeability of this candidate. To enhance the permeability characteristics of this candidate, the gradation is more uniformly graded where the slope of the gradation is about $C_z = 2$. To meet this slope, **Bar LM** is set above **Point A**. The remainder of the curve is set to a slope slightly less than $C_z = 2$ and curves to the left. As mentioned earlier, this type of gradation could be used in toe drains on pervious foundations, as well as blanket drains on similar foundations.

5.4.8.3 Transition Zone Filter

Figure 5.4.8.3-1 illustrates a broadly graded material that could be used as a chimney transition zone. The advantage of this gradation is in the economy of production since a wider range of grain sizes are used for a single zone. Note that while the candidate gradation defers to the particle retention criteria (set to the minimum D_{15} limit near point B), the coarser sizes are set to the maximum limit

(**Points J** and **K**), hence spanning the entire range within the limits. This candidate has a coarser upper end than more uniformly graded candidates, permitting a minimum 1-inch material for the next transition zone. The reduction in the number of zones also results in a lower cost. While this gradation is more susceptible to segregation than more uniformly graded material, that amount of segregation is manageable using the construction techniques described in section 5.8.3.

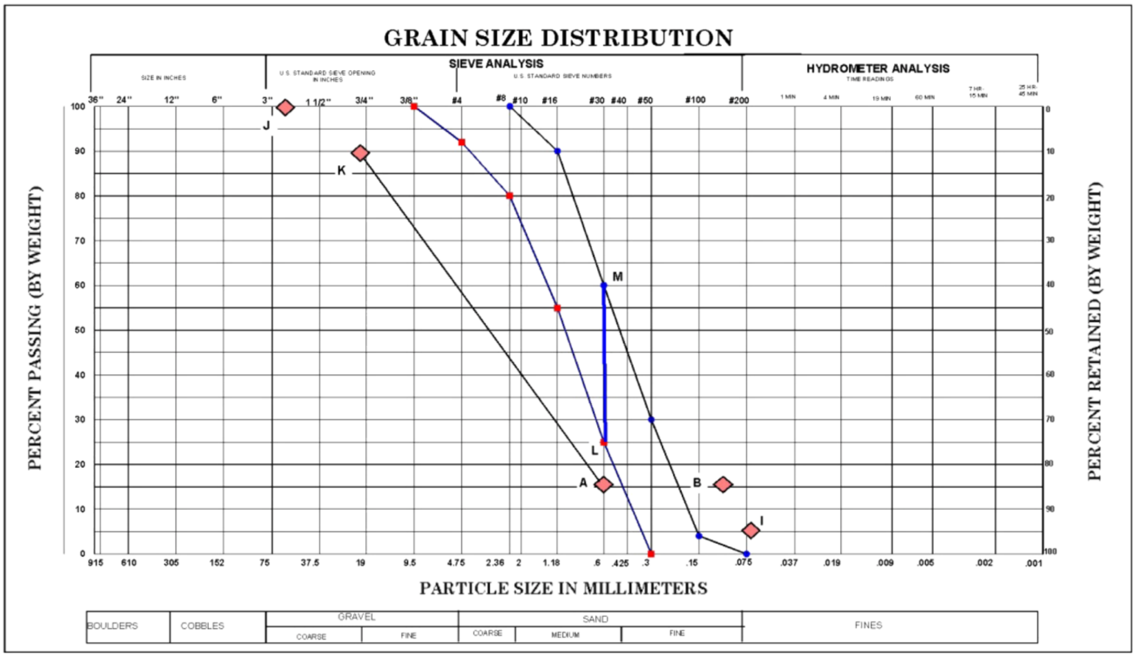

Figure 5.4.8.2-1. Example drainage filter gradation.

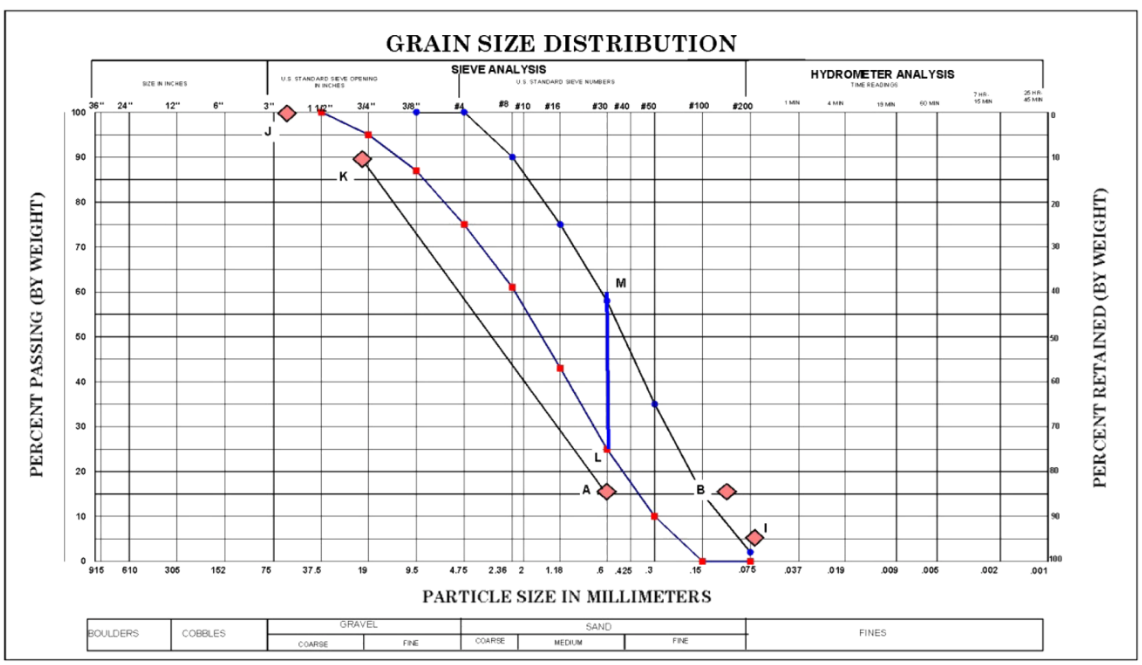

Figure 5.4.8.3-1. Example transition zone gradation.

5.4.8.4 Standard Material Filter

Figure 5.4.8.4-1 illustrates the use of modified C-33 concrete sand, which is commercially available in most areas. This gradation was plotted as a reference within the limits derived from the design procedure. Since it is within the limits, this material would be acceptable for use in this Category 2 base soil. Note that the limit on the fines content is in addition to what is in the C-33 designation.

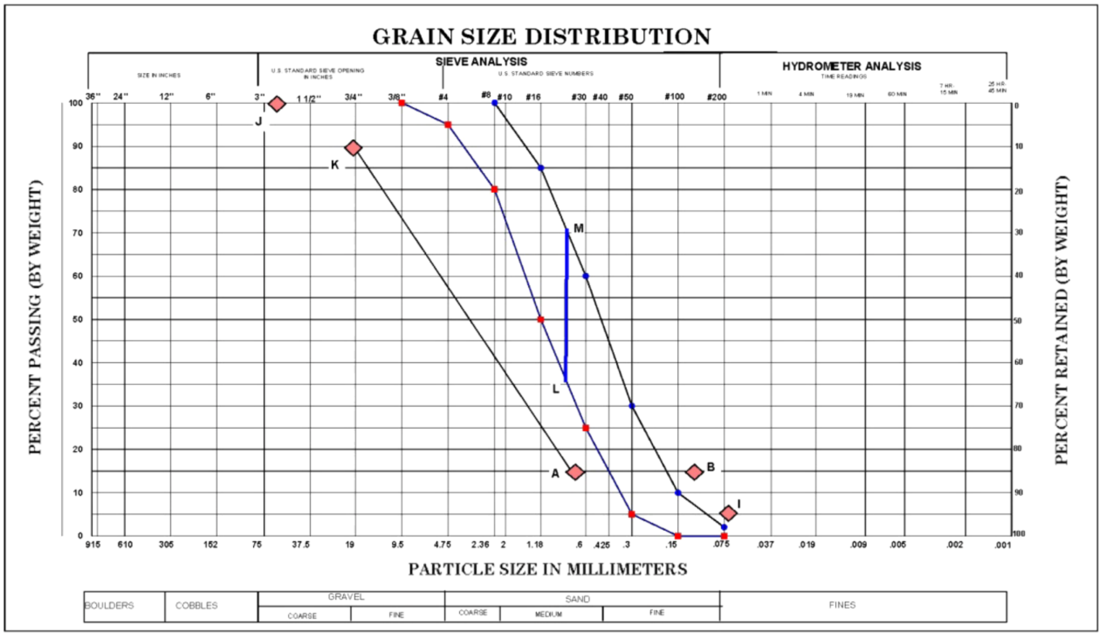

Figure 5.4.8.4-1. Example standard material (C-33, modified concrete sand).

5.5 Drain Envelopes and Drain Pipes

Drain envelope, or envelope, is a second stage filter placed between the drain pipe and first stage filter which is placed against and protects the foundation. The gradation selection procedure described in the previous section is used to determine the envelope gradation. In this arrangement, the first stage filter now becomes the base soil and the envelope becomes the filter.

5.5.1 Drain Envelope Thickness and Gradation

Drainage materials surrounding the drainpipe should have a minimum thickness equal to 12 inches. The ease of placement and inspection of the filter and drainage material around a drainpipe should serve as a guide to the designer on setting the thickness of these materials. The above thicknesses may need to be increased for more difficult placements and inspection situations.

When using the criteria in section 5.5 for designing a second-stage filter, which usually is thought of as a drainage layer or zone, it is possible to increase the ratio of D15F to D85B over that used for protecting a natural or unprocessed soil. The ratio can be as high as 9, but 5 is generally found to meet the practical requirements of the situation. This increase is sometimes possible because the first-stage filter: (1) is a material processed to stringent gradation requirements and placed and compacted under controlled conditions, (2) is inspected and tested to verify that material properties conform to those that are specified, (3) usually has seepage gradients that are much less than those of a foundation material or impervious zone that needs filter protection, and (4) has D_{85} particles in the first stage filter material that are larger than those in materials that are usually being protected and, therefore, less likely to move. However, this increase should be made with caution.

5.5.2 Drain Pipe Perforation Size

The maximum pipe perforation dimension[19] should be no larger than the finer side of the $D_{50}E$ where $D_{50}E$ is taken from the gradation of the envelope (drain) material that surrounds the drainpipe. That is:

$$\text{Max Perforation Dimension} \leq D_{50}E$$

It is emphasized that inaccessible drainpipes beneath embankment dams should be avoided. Drainpipes should be sized and located, and inspection wells should be provided so that access for inspection, maintenance, and repair, if necessary, is easy. It is recommended that each pipe segment be accessible from both ends. In order to provide a margin of safety for the pipe capacity, drains should be sized so that the depth of water in the drainpipe is less than 50 percent of the inside diameter of the drainpipe at the maximum expected discharge. If it is anticipated that the drainpipe will collect a large amount of flow from a pervious foundation or embankment, the maximum depth of water should not exceed 25 percent of the inside pipe diameter due to uncertainties in predicting the amount of flow.

5.6 Laboratory Test Procedures

In the following section, test procedures for laboratory tests are presented. The procedures have been separated into two categories: particle retention and material quality. The particle retention tests evolved from the original test procedures used during research into particle movement. The material quality tests come mainly from industry standard tests, although one stems from research work.

[19] The maximum dimension as used in this standard is the width for a slot and the diameter for a hole.

5.6.1 Tests for Particle Retention

As described in section 5.1.7, laboratory studies have been used historically to obtain empirical relationships related to soil particle retention. This section summarizes and compares these test procedures.

Experiments on filter compatibility were conducted by Sherard for silts and clays [43]. In this study, intact specimens of silt and clay that were 30 to 60 mm (1.18 inches – 2.36 inches) thick were compacted against filters, some of which were significantly coarser than filter criteria would allow. The tests began with hydraulic gradients in the range of 167-333. At these gradients, failures in the base specimen could not be induced because the discharge energy at the filter/base interface was insufficient to initiate internal erosion. Only when applied gradients were increased and hydraulic fracturing was induced were failures initiated. Based on these results, Sherard developed an alternative test that used a preformed slot or hole in the base soil. This was preferred because the flow path is more precisely defined. The early experiments used a slot with dimensions of about 12 mm x 1.5 mm. The length of the base soil specimen was about 6.5 inches (165 mm), and the filter section was about 3 inches (76 mm) long.

5.6.1.1 No Erosion Filter Test

Outgrowth of the initial test program was the development of the No Erosion Filter (NEF) test. The following summary and conclusions from Sherard's (1989) paper, "Critical Filters for Impervious Soils," explains the change in experimental apparatus. Figure 5.6.1.1-1 is reproduced from Sherard's publication, *Filters for Silts and Clays* [43].

> "1. The NEF test is the best available test for evaluating critical filters located downstream of impervious cores in embankment dams. This is considered the most valuable single conclusion from the four-year long research effort. The conditions in the test duplicate the most severe conditions that can develop inside a dam from a concentrated erosive leak through the core discharging into a filter. For tests with filters finer than the filter boundary (D_{15} smaller than D_{15b}), there is no visible erosion of the walls of the initial preformed leakage hole passing through the base specimen.
>
> 2. The NEF test is a simple test that can be made in any soil mechanics laboratory. It gives reliably reproducible and easily interpreted results, and it is well adapted for testing the entire range of impervious soils used for dam cores.
>
> 3. The filter boundary D15b separating successful and unsuccessful tests for a given impervious soil, as determined by the NEF test, is unique. The boundary D15b is independent of the dimensions of the laboratory apparatus and is dependent only on the properties of the protected impervious soil (base). The filter boundary D15b can be considered a property of the base soil in the same sense that results of tests to

determine the Atterberg limits and effective shear strength parameters are considered properties of the impervious soil.

4. Based on the results of NEF tests, soils used for the impervious sections of embankment dams fall into the four general categories shown in Table 1 depending only on fine content." [20]

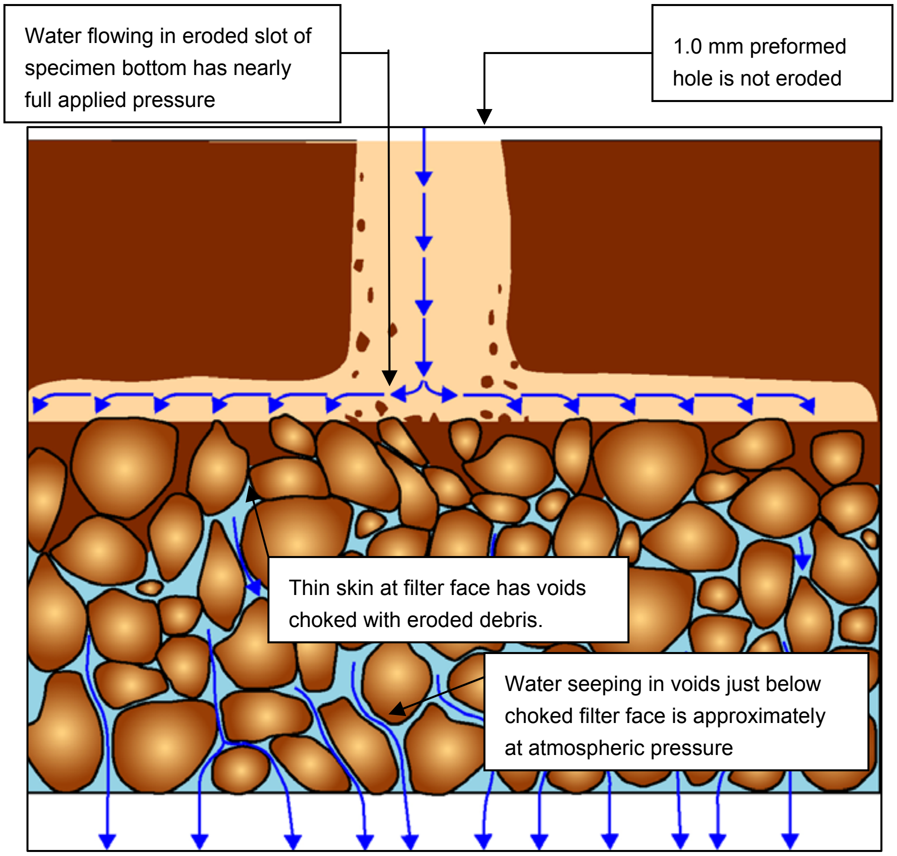

Figure 5.6.1.1-1. Illustration from Sherard [43]. This sketch illustrates how a filter seal develops as eroded particles are carried from the sides of a crack in the base soil to the filter face. Eroded particles accumulate and create a filter seal that effectively blocks further flow and subsequent particle movement.

The NEF Test apparatus and procedures are described in "Filters and Leakage Control in Embankment Dams" [44]. A schematic of the test is reproduced in figure 5.6.1.1-2. The Reclamation procedure for performing this test is USBR 5630-89 as described in the *Earth Manual* [1].

[20] See section 5.4.3 in this document for an explanation of these categories.

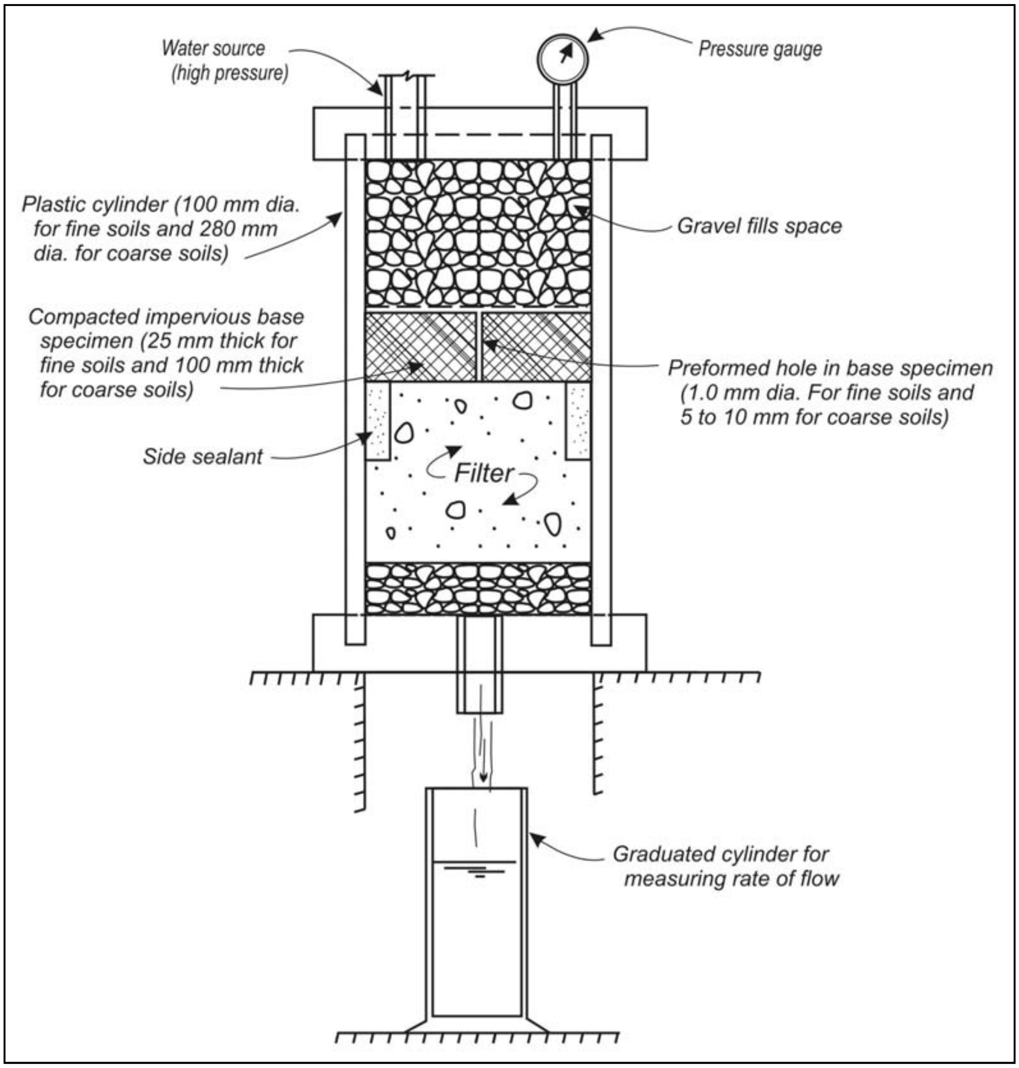

Figure 5.6.1.1-2. NEF Test apparatus.

5.6.1.2 Continuing Erosion Filter Test

Foster, Fell, and Spannagle [45, 46] presented a modification to the NEF test known as the Continuing Erosion Filter (CEF) Test. The device used by Foster, Fell, and Spannagle to evaluate the potential for continuing erosion is shown in figure 5.6.1.2-1. Note that NEF tests can still be performed in the CEF device.

The following modifications were made to the NEF Test during the development of the CEF test:

- Water passing through the filter during the tests was collected, and the eroded materials were dried and weighed to determine the loss of base soil required to seal the filter.

- Progressively coarser filters were used until the filter was not sealed.
- Thicker base specimens were used to allow for greater erosion losses.

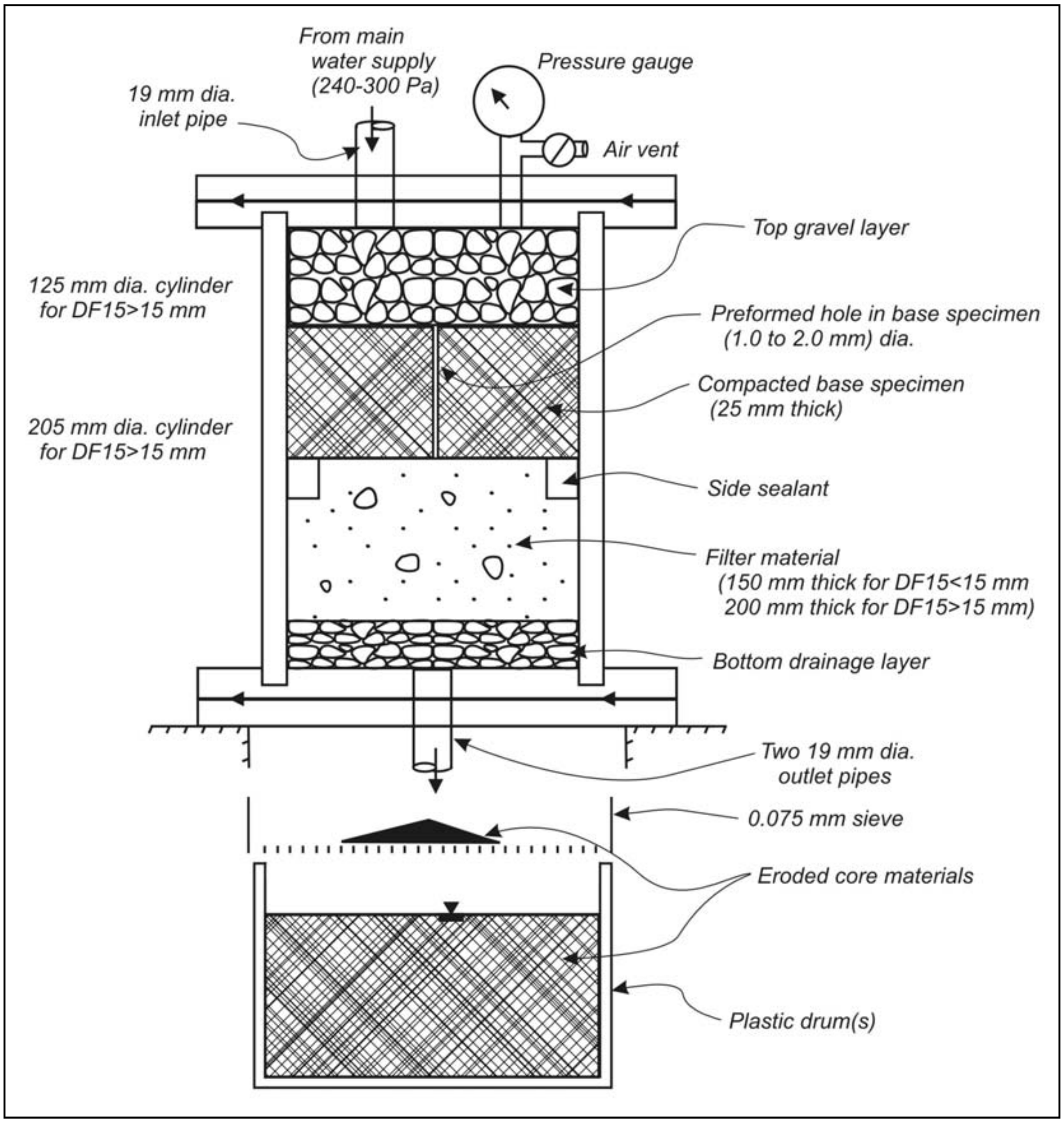

Figure 5.6.1.2-1. CEF Test apparatus.

This study determined partial and continuous erosion thresholds based on grain size distribution. They recommended evaluating an existing embankment filter differently than when designing a new filter. The following quote is from their article:

"An assessment of existing filters should consider how the filter may perform in the event of a concentrated leak developing through the core. The performance of filters in dams is classified into three categories as follows:

- Seal with no erosion-rapid sealing of the concentrated leak, with no potential for damage and no or only minor increases in leakage

- Seal with some erosion-sealing of the concentrated leak but with the potential for some damage and minor to moderate increases in leakage

- Partial or no seal with large erosion-slow sealing or no sealing of the concentrated leak, with the potential for large erosion losses, large increases in seepage, and the development of sinkholes on the crest and erosion tunnels through the core."

5.6.1.3 Rate of Erosion Test

Subsequent research at the University of New South Wales [34] has involved the use of similar experimental setups to study the rates of erosion of soils in which a successful filter is not present. This research focused primarily on the issue of base soil erosion, especially the susceptibility of a given soil to internal erosion. They describe two laboratory tests that were developed for this study. Also during the study, they examined the critical hydraulic shear stress necessary to initiate internal erosion. These two tests are: (1) the Hole Erosion Test (HET) and (2) the Slot Erosion Test.

The HET uses a 6-mm (0.24-inch) hole drilled in a specimen to model the erosion occurring in an embankment. This contrasts with the 1 mm size of hole used in the NEF Test. The HET tests used head differentials of 50 to 1,200 mm (2 inches to 4 feet), whereas the NEF Test used 138 feet of head.

Reclamation became interested in this research for use in risk analysis. Reclamation, as well as other agencies, participated in this research, especially the transition from the hole erosion setup to the slot erosion method [47].

5.6.2 Tests for Material Quality

This section describes tests that may be used to evaluate the quality of proposed filter materials. Since a critical feature of a filter is to protect against cracks in the base material, it is imperative that the filter itself not sustain a crack. Historically, material quality testing of filters has concentrated on fines content and plasticity of those fines. This was done by using conventional test procedures for gradation analysis (ASTM C117) and plasticity (ASTM D4318). Recent as-built filter performance has indicated that other types of binders, such as soluble minerals, may also contribute to adhesion in filter materials and that these binding agents may not be detected by conventional test procedures. Therefore, in addition to the conventional test procedures, additional tests are included in this section to more closely evaluate material quality. It is recognized that some of these procedures have not been in general use in the profession, and some do not have an accepted standardized test procedure.

A particularly good example of the detrimental effect of binding agents can be found in recycled concrete. This material, produced by crushing existing concrete such as paving, is popular for use as a concrete aggregate. Since the gradation range of concrete aggregate is often acceptable as a filter or drain material, it may be attractive to use this in embankment dam construction. However, this material is unacceptable from a quality standpoint because the cement continues to hydrate, even many years after initial placement. This hydration can lead to the material obtaining strength and, subsequently, sustaining a crack. Therefore, aggregate derived from concrete recycling should never be used for filter or drain material in embankment dams.

Filter and drain materials are derived from clean sands and gravels similar to aggregates (sand and gravel) that are used for production of concrete. It is not surprising then that material quality testing used for aggregates can also be used for filter and drain material. A variety of tests are available to evaluate aggregate quality. It is noted that independent of material testing, qualitative statements have been used in specification paragraphs for both aggregates and filter/drain material. A typical specification statement, as presented by the Federal Highway Administration [48], is:

> "Aggregates used in concrete mixtures for pavements must be clean, hard, strong, and durable and relatively free of absorbed chemicals, coatings of clay, and other fine materials."

Similar statements have been used in Reclamation specifications, and they may inform the contractor of intent, but it is difficult to enforce since the requirement is subjective. The test procedures presented in this section are beneficial in specifying the quality requirements for a given material. The use of subjective statements in specification paragraphs should be avoided.

5.6.2.1 Sampling

The first step in testing candidate materials is to collect the sample. It is important that a representative sample be collected in accordance with ASTM D75, "Standard Practice for Sampling Aggregates" and USBR 7000 [1]. The sample must be large enough to represent the material accurately; collection of undersized samples is a common problem within the practice. ASTM D75 includes minimum sizes of samples of aggregates as shown in table 5.6.2.1-1.

Table 5.6.2.1-1. Minimum sampling size based on maximum particle size

Maximum size of aggregate (mm)	Minimum sample size (kilograms)	Minimum sample size (pounds)
Fine aggregate		
2.36 mm (No. 8 sieve)	10	22
4.75 mm (No. 4 sieve)	10	22
Coarse aggregate		
9.5 mm (3/8 inch)	10	22
12.5 mm (1/2 inch)	15	33
19.0 mm (3/4 inch)	25	55
25.0 mm (1 inch)	50	110
37.5 mm (1.5 inches)	75	165
50 mm (2 inches)	100	220

5.6.2.2 Tests for Clay Lumps and Friable Particles

American Association of State Highway Transportation Officials (AASHTO) Test T112 and ASTM C142 are used to determine the presence and amount of clay lumps and friable particles in a soil sample. Samples are soaked 24 hours in distilled water, and any particles that can be broken by finger pressure and removed by wet sieving are classified as clay lumps or friable material. For aggregate acceptability, ASTM C-33 allows no more than 3 percent clay lumps or friable particles as measured in this test. When C-33 quality requirements are included in filter quality specification paragraphs, this requirement must be met.

5.6.2.3 Soundness Tests

One test for particle soundness is ASTM C88, "Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate." For acceptability, ASTM C-33 limits the average loss during five cycles of the soundness test to 10 percent when sodium sulfate is used or 15 percent when magnesium sulfate is used. When C-33 quality requirements are included in filter quality specification paragraphs, this requirement must be met.

Another particle soundness test is ASTM C 131, "Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine," more commonly known as the "LA Abrasion Test." For acceptability, ASTM C-33 requires no more than 50-percent loss during abrasion tests. When C-33 quality requirements are included in filter quality specification paragraphs, this requirement must be met.

5.6.2.4 Tests for Plasticity of Fines

Plasticity cannot be determined by grain size alone. For this reason, filter specifications often contain language concerning the plasticity of any fines in the sample. Specifications commonly require that any fines in the filter be nonplastic as measured in ASTM Standard Test Method D4318. This test for plasticity requires obtaining at least 20 grams of material finer than the No. 40

sieve[21]. Usually, the only portion of the test required is the plastic limit test. It is only necessary to demonstrate that the sample cannot be rolled to a 1/8-inch-diameter thread at any water content.

5.6.2.5 Sand Equivalent Test

The ASTM test procedure for the "Sand Equivalent Test" is described in ASTM D2419, and the AASHTO Standard Test Method is T 176. The Sand Equivalent Test is used to determine the relative proportions of fines or claylike material in fine aggregates. Aggregate passing the 4.75-mm (No. 4) sieve is placed in a graduated, transparent cylinder that is filled with a mixture of water and a flocculating agent. After agitation and 20 minutes of settling, the sand separates from the flocculated clay, and the heights of sand and clay in the cylinder are measured. The sand equivalent is the ratio of the height of the sand to the height of clay multiplied by 100.

$$\text{Sand}_{\text{height}} / \text{Clay}_{\text{height}} \times 100 = \text{SEV}$$

A higher sand equivalent value (SEV) indicates a cleaner aggregate. Minimum specified SEVs for fine aggregate in asphalt mixtures range from 25 to 60. Concrete aggregate specifications commonly require a value to be above 70 or 80. A value greater than 80 should be used for filter material.

5.6.2.6 Petrographic Analysis

Petrographic analysis can be used for evaluating aggregates proposed for filter material. ASTM C295, "Standard Guide for Petrographic Examination of Aggregates for Concrete," provides documentation of the quality of aggregates used for filters. Factors evaluated in the procedure include:

- Whether the aggregate contains chemically unstable minerals including soluble minerals such as carbonates
- Whether the aggregate particles are composed of weathered particles
- Determination of the proportions of cubic, spherical, ellipsoidal, pyramidal, tabular, flat, and elongated particles in an aggregate sample or samples
- Identification of potentially alkali-silica reactive and alkali-carbonate reactive constituents, determination of such constituents quantitatively, and recommendation of additional tests to confirm or refute the presence in significant amounts of aggregate constituents capable of alkali reaction in concrete

[21] Note that it may be difficult to conduct a test on material finer than the No. 40 sieve in this situation. If so a sample of material finer than the No. 200 sieve can be used. If this modified procedure is used it should be made clear in the specification paragraphs that the test procedure deviates from ASTM D4318.

- Identification of contaminants in aggregates, such as synthetic glass, cinders, clinker, coal ash, magnesium oxide, calcium oxide, etc.

These factors are important for material quality in filters because they typically indicate when binding agents may be present. Chemically unstable minerals, or minerals that can go into dissolution, can be redistributed through the soil mass and coat larger pieces of aggregate, binding them together. A similar process can occur through alkali reaction.

The assessment of particle weathering and particle shape provides an indication of particle strength. Weathered particles will be weaker than particles that have experienced little weathering. Particles exhibiting a more cubicle shape will also be stronger than flat, tabular, ellipsoidal, spherical, and elongate shapes.

ASTM Standard Test Method C-294, "Standard Descriptive Nomenclature for Constituents of Concrete Aggregates," is also useful in documenting aggregate properties. It includes thorough descriptions of the various rock types commonly used in the production of aggregates.

5.6.2.7 Sand Castle Test

Vaughan and Soares [49] introduced a test to evaluate the self-healing properties of a filter zone in an embankment dam. Their interest in self-healing properties arose from the problems that developed at the Balderhead Dam in England. Vaughan proposed a test (sometimes referred to as the Sand Castle Test) to evaluate the cracking potential of filter material. Vaughan discusses this as follows:

> "For a filter to be effective if cracks form, it is necessary for it to be noncohesive. If it is not, then it may itself sustain an open flooded crack without collapse and so fail to protect a cracked core. The inclusion of more fines in a filter to enable it to retain material of clay floc size may give it cohesion."

Vaughan goes on to describe a test that he recommended to evaluate this property as:

> "A simple test, suitable for use in a field laboratory, has been devised to examine filter cohesion. It consists of forming a cylindrical or conical sample of moist compacted filter, either in a compaction mould, or in a small bucket such as is used by a child on a beach; standing the sample in a shallow tray (if a bucket is used the operation is exactly as building a child's sand castle) and carefully flooding the tray with water. If the sample then collapses to its true angle of repose as the water rises and destroys the capillary suctions in the filter, then the filter is noncohesive. Samples can be stored for varying periods to see if cohesive bonds form with time. This test is, in effect, a compression test performed at zero effective confining pressure and a very small shear stress, and it is a very sensitive detector of a small degree of cohesion."

USACE adopted this test in EM 1110-2-1901, "Embankment Seepage Control," with the following description:

> "Also, the amount and type of fines present influence the capacity of a filter to self-heal by collapsing any cracks within the filter (see figure 8-3) [figure 5.6.2.7-1 in this document]. Therefore, the maximum percent fines and type (silt, clay, etc.) to be allowed in the filter of an earth dam must be shown to be sufficiently pervious by laboratory filter tests (I) and self healing by collapse tests" [50].

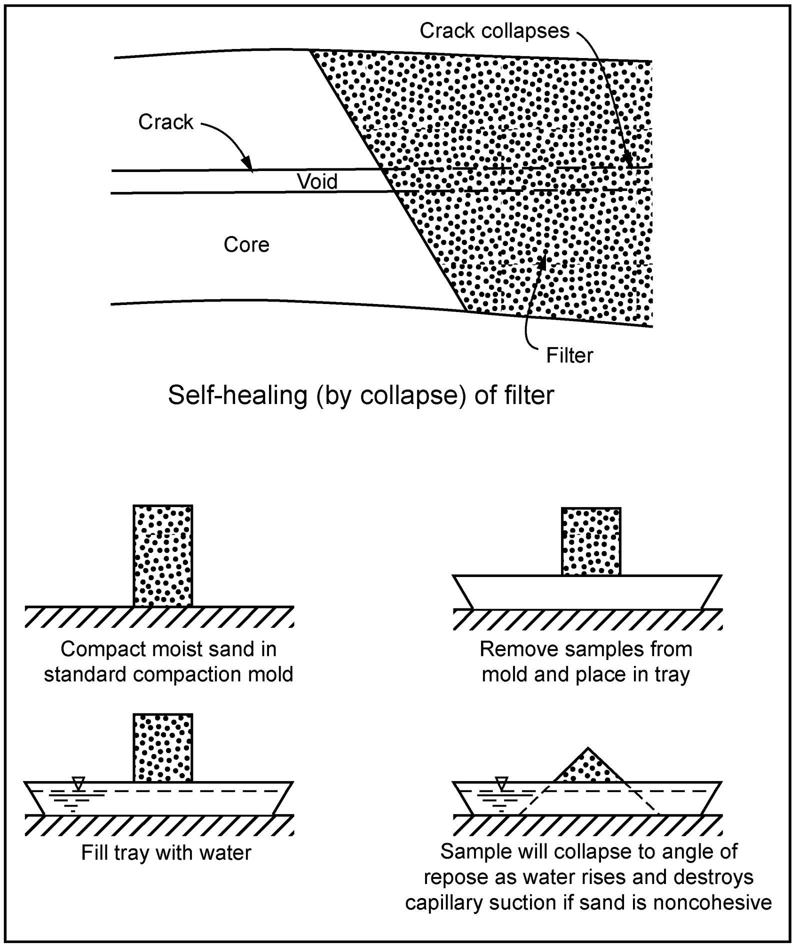

Figure 5.6.2.7-1. Figure 8-3 from USACE Engineering Manual EM 1110-2-1901. The figure illustrates the Vaughan Test.

Photographic results of successful and unsuccessful material performance based on the USACE procedure are shown in figures 5.6.2.7-2 and 5.6.2.7-3, respectively.

The lack of precision and the inability to express results quantitatively are shortcomings of this test. Specimen preparation has also been identified as an issue. Because of these concerns, Reclamation has undertaken a study to see if the test procedure could be improved [47a]. A more specific preparation method was developed as part of the study. In the revised procedure, the specimen is oven dried at 120 degrees Fahrenheit (°F) until its weight stabilizes. This step was added because, by observation, it has been noted that filter material placement in the field can be exposed to drying and warm summertime temperatures between placements, sometimes for several days. It is thought that these conditions may contribute to forms of physiochemical bonding between soil grains.

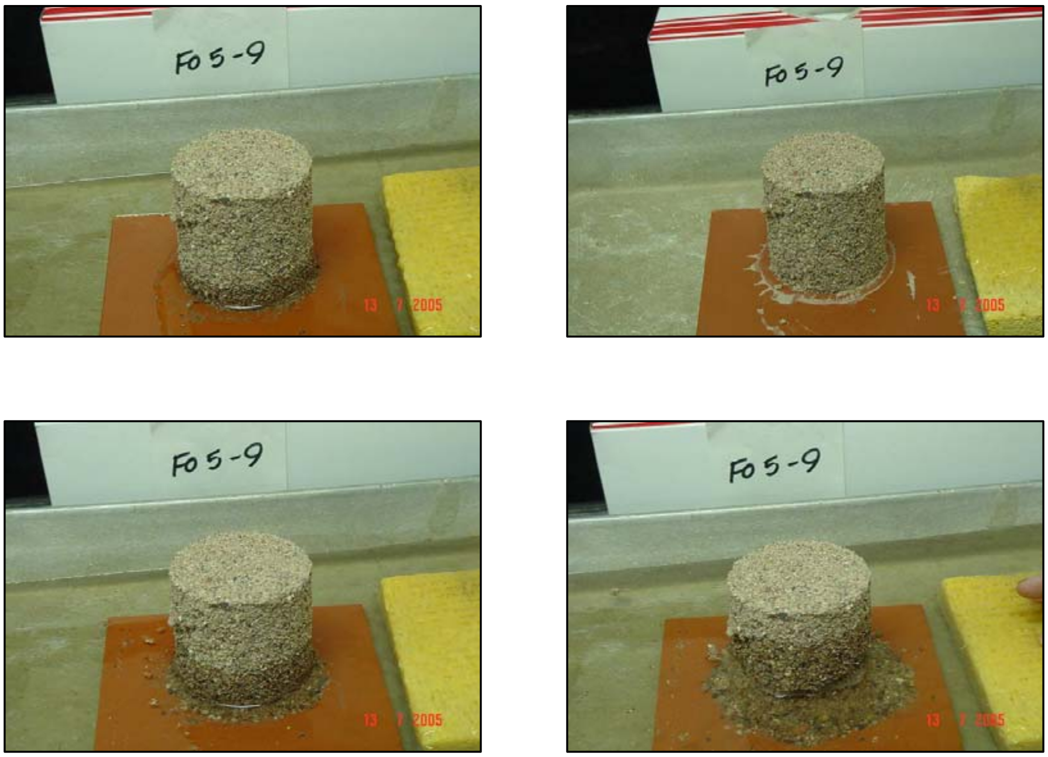

Figure 5.6.2.7-2. Illustration of relatively poor self-healing behavior. The sample does not collapse well after 50-percent submersion.

After curing, the samples are placed in water and the time to collapse is recorded. The curing step appears to be the critical element in making the Sand Castle Test sensitive to the conditions experienced by filter material in the field.

5.6.2.8 Compressive Strength Test

Cementing of filters by drying, as described in the previous paragraph, can lead to a filter sustaining a crack rather than protecting against one. Using the revised procedure from the Sand Castle Test, a sample that has been cured at 120° F can be tested in unconfined compression. After curing, the specimen is tested in accordance with ASTM D2166-06, "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil," as opposed to the soaking procedure used in the Sand Castle Test.

Figure 5.6.2.7-3. Illustration of relatively good self-healing behavior. The sample collapses relatively quickly as it is submersed.

5.7 Material Sources

In general, there are two potential sources for filter/drain material. These are undeveloped sources and existing commercial sources. For small dams, it may be cost effective to use commercial sources; for larger projects, it may be more economical to develop a new source specifically for the job if suitable undeveloped material exists near the jobsite. The availability and suitability of material must be factored into the design. For example, if suitable material is limited in quantity or expensive to obtain, it may be more economical to use thin or narrow zones (less than placement equipment width) and more intensive placement and inspection techniques to ensure construction of adequate filter/drain zones. On the other hand, if ample material is near the jobsite and can be economically developed, equipment width dimensions of filter/drain zones with less intensive placement and inspection techniques may be more cost effective. The designer must ensure that there is sufficient volume available to construct the work. Generally, it is prudent to have at least two to four times the volume of material available in borrow than is necessary to produce the final in-place volume of the filter/drain zones. For large jobs, a sieve-by-sieve analysis should be made to determine which grain sizes are critical for a specific pit. If thinner zones are used, the dimensions must be checked for adequate hydraulic capacity. Logical sources must be investigated and, for approved sources, appropriate information such as location, availability, ownership, drill logs, test pit logs, appropriate lab tests, and geotechnical considerations provided in the specifications. Refer also to Chapter 10, "Embankment Construction," [51] and Chapter 12, "Foundation and Earth Materials Investigations," [52] of this design standard.

The information included in the specifications should be adequate to allow bidders to develop reliable costs for preparing their bid. Borrow area information for approved borrow sources must be sufficient for the bidders to design an effective processing plant. The range of material gradation in the borrow area must be determined and this information clearly conveyed in the specifications so that the processing plant can be designed with sufficient flexibility to handle the range of material and effectively produce the required material. Plants without this flexibility have been the cause of some large changed condition claims from contractors who argued that information furnished was inaccurate or insufficient and misled their plant design E.

5.7.1 Onsite Material Sources

Logical sources must be investigated and, for approved sources, appropriate information such as location, availability, ownership, drill logs, test pit logs, appropriate laboratory data, and geotechnical considerations provided in the specifications.

The first step in identifying undeveloped sources is to perform a literature review. Existing literature will be the quickest way to find possible borrow areas. These sources include topographic maps (also known as "quad" sheets), soil reports, and regional geology reports. Quad sheets (U.S. Geological Survey [USGS] quadrangle maps) of the local area can be obtained and examined for existing or historic quarries, indicated by a mining symbol (a pair of crossed picks). Also available to the general public are NRCS (formerly Soil Conservation Service) soil reports (also known as soil surveys). These reports, produced for almost every county in the United States, contain soil maps of the county, as well as the engineering properties for those soils. While the soils are described in agronomic terms, the information is still valuable for engineers. Also available, but not uniformly produced, are Pleistocene (or Quaternary) geologic reports produced by the USGS, universities, and other interested parties. While these reports may not identify specific borrow area locations, they are instructive in explaining the geologic setting of the area and indicate promising locations to examine more closely.

After completing a literature review for the area, a terrain interpretation step should be undertaken. Terrain interpretation can be done two ways: by aerial photography and by site reconnaissance. Terrain interpretation of photographs is described in several text books [53, 54], where a description is given of changes in vegetation and land use that often indicate what soils are present.

When site reconnaissance is undertaken, an easy way to identify soil profiles or other erosional features is by road cuts and naturally occurring cuts. Figure 5.7.1-1 illustrates a moraine that has been dissected by a creek and provides an early indication of the underlying stratigraphy.

Figure 5.7.1-1. Exposed moraine cross section showing till overlying glacial outwash. Such exposures provide an opportunity to obtain geologic information by observation.

In general, sand and gravel deposits are associated with the following geologic features:

- Alluvium along watercourses
- Glacial outwash deposits
- Alluvial fans

Also critical for borrow area characterization are the groundwater conditions. Since excavation techniques will be different above and below the water table, a clear understanding of this level, and its fluctuations, is necessary. If dewatering is required for borrow area use, the cost will need to be factored into the project estimate. Consideration also needs to be given to seasonal fluctuations in water levels. Providing a single static level to bidders can result in a claim if the ground water level rises later and floods out the contractor. Therefore, water level readings should be collected for the full range of expected water levels and presented in the specification.

Common exploration methods for borrow area studies include augering, trenching, bucket augering, and test pits. Which method is used is dependent on the maximum particle size of the in situ material and material variability. Material that is smaller than 3 inches should be sent to the laboratory for gradation analysis. Large material is typically estimated visually in the field. It is imperative to present the full range of material sizes because history shows that claims are made on this critical characterization.

The preferred exploration method for sand and gravel borrow areas above water table is trenching. Trenches are usually excavated using a utility tractor or trackhoe (excavator), although larger trenches may be excavated by a dozer. Initially, trench side slopes should always be vertical to give the best representation of the material. For safety reasons, personnel should not be allowed in vertical-sided trenches greater than 3 feet deep. Figure 5.7.1-2 illustrates a technique that can be used to excavate an exploration trench that can be entered for mapping and sample retrieval.

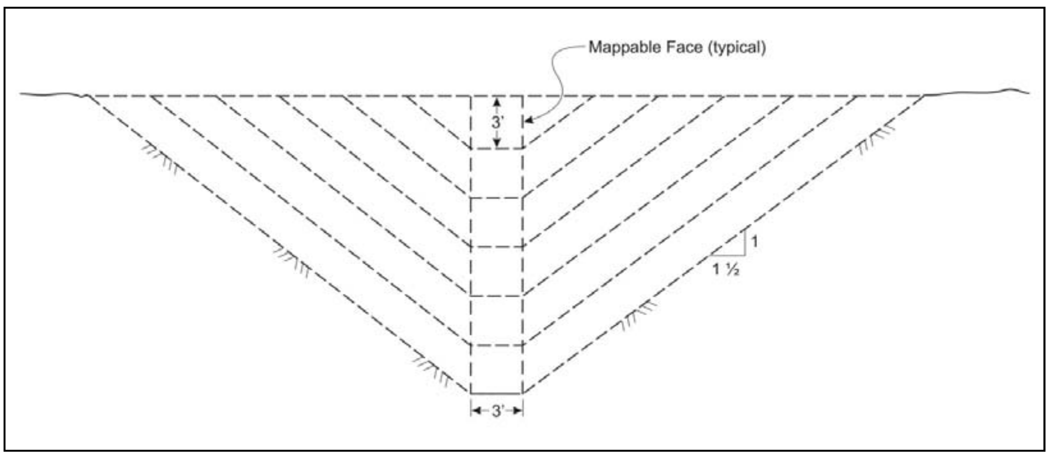

Figure 5.7.1-2. Exploration trench excavation sequence.

When sampling from trenches, all material should be collected, including oversized material, so that the percentage of oversized material in the borrow can be estimated. When cobbles and boulders are present, their volume will have to be estimated visually in the field. Typically only material less than 3-inches is taken to the laboratory for analysis. Figure 5.7.1-3 shows a trench excavation with the boulders set to one side of the trench, indicating the size and distribution of the boulders. Figure 5.7.1-4 shows the material distribution in the trench wall, including interbedding. Note that this trench wall gives a much more detailed description of the materials than what would be obtained from drill hole or auger data. When sampling below the water table bucket auger may be required.

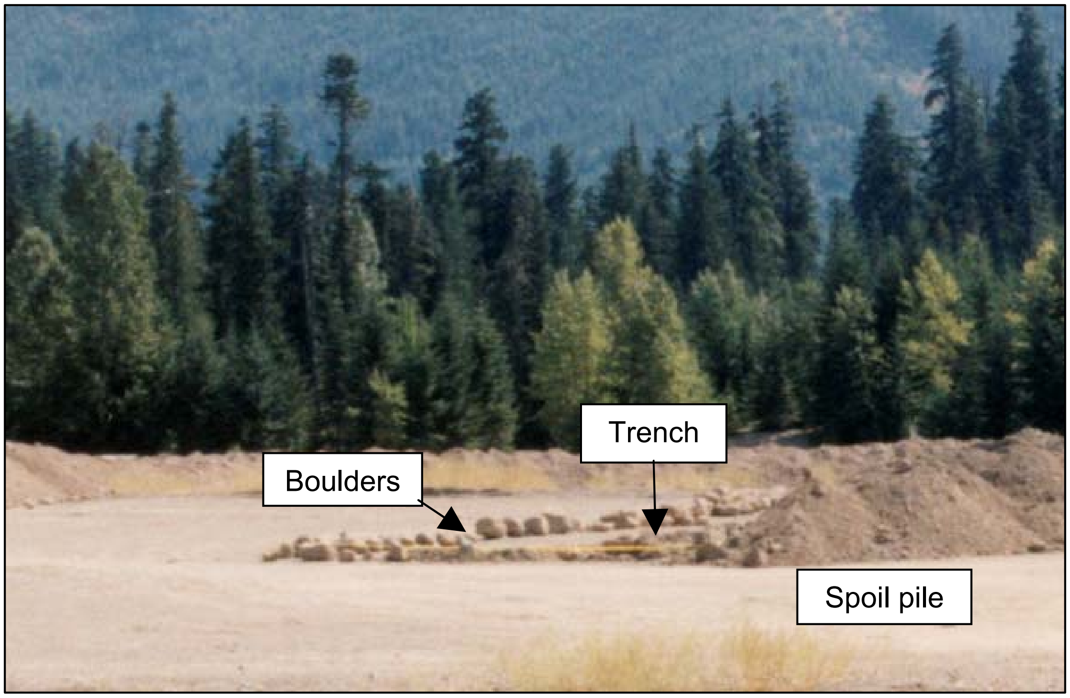

Figure 5.7.1-3. Exploratory trench excavated at a potential borrow area. During the excavation, the boulder-size material was set aside to better characterize the deposit.

5.7.1.1 Lack of Suitable Clean Materials

While sand and gravel soils are ideal for production of filters and drain materials, they are seldom found "clean" in situ. Usually, some amount of fine material (soil finer than the No. 200 sieve) will be present in the deposits. Typically, the amount of fines present will define whether the pit is acceptable or not. Commonly available processing plants can economically process raw material with about 8 percent fines content (based on a sample with material greater than 3 inches in diameter removed). The fines content of the material that comes out of the plant (in stockpile) should not be greater than 2 percent. A number of washing operations are available, including spray bars, sand screws, sluice trays, etc., to remove these fines. These methods are successful when the fines are evenly distributed throughout the raw material. Borrow areas with layers of clay or silt may make the area unusable. The elevation and thickness of the layer or layers will influence whether or not a borrow area will be usable. A layer on the ground surface can be readily stripped and wasted prior to excavating the desired underlying sand and gravel deposits. The limiting thickness of an overlying layer will be a function of the cost analysis described earlier. Layers throughout the pit are more difficult to analyze. Thin layers, less than 1 inch in thickness, may be acceptable if the blended fines content for the mass is less than 8 percent. That is, numerous 1-inch layers or a high percentage of 1-inch layers may make a borrow area unacceptable. Situations in which layers are several feet thick and at depth within the pit usually will render the pit unusable. Since pits are typically excavated from a vertical face, either from the top using a trackhoe (excavator) or from the bottom using a loader, the low-quality layer will contaminate each load. In some instances, it may be possible to excavate a desirable layer and send it to the processing plant, excavate an undesirable layer to waste, and then return to excavating the underlying desirable material. This operation will have the added cost of either stockpiling the upper clean layer before feeding it to the processing plant or shutting down the plant while the undesirable layer is removed.

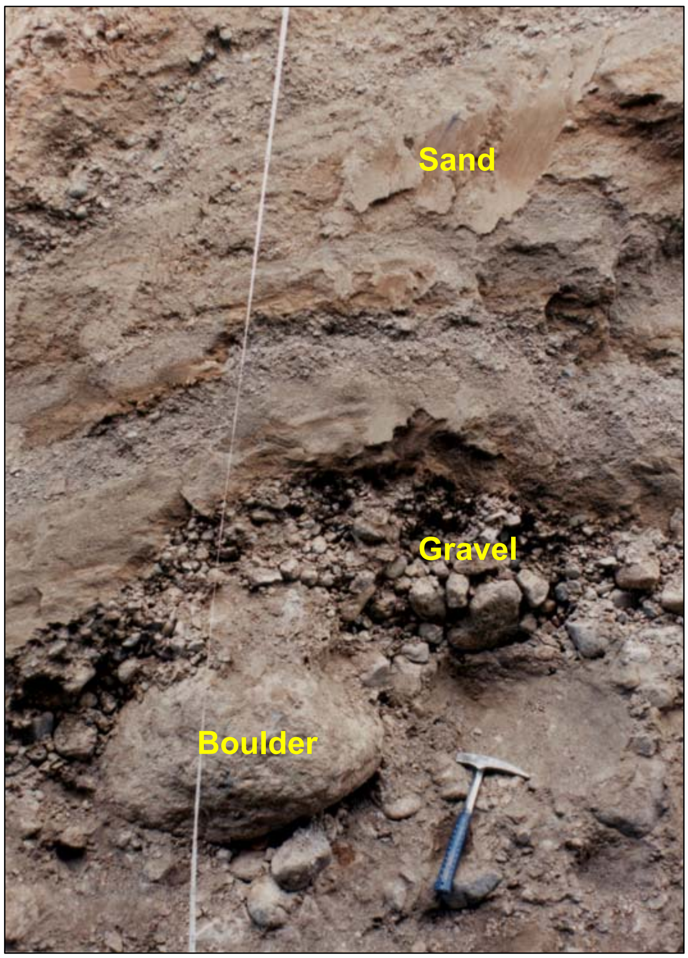

Figure 5.7.1.4. Exposed vertical trench face indicating the stratigraphy of a potential borrow area. This type of exposure provides a level of information not available by exploratory drilling.

In addition to fines occurring in discrete layers, problems can also arise from fines adhering to larger particles such as gravel and cobbles. During borrow investigation, larger particles should be specifically examined for fines adhesion.

As a general rule, fines that are easily wiped off of the larger particles by hand can be successfully washed in the processing plant. Fines that can only be removed with effort by rubbing cannot be cleaned by any type of washing operation. This condition is usually only found above the ground water table, and similar material below the water table has a better likelihood of being washed. In this situation, the material above the water table may be unusable, even if the fines content is less than 8 percent.[22]

Along with considering the amount of fines in a potential pit, the quality of the aggregate should also be determined. See section 5.6.2 for a description of the quality requirements for filter and drain materials and the test methods that can be used to meet these quality requirements.

5.7.1.2 Processing Plants for Filter Materials

Processing plants consist of three major operations: raking, screening, and washing. The raking operation removes all oversize material, typically material larger than 3 inches. Raking can be done in the borrow area by running a rake through the excavation surface, which picks out the oversize material; at a loader with a skeleton bucket, which retains the oversize material; or at the initial feed into the plant through a feed box, which has a grate set to the desired size limit.

Screening operations consist of mechanical screening using a number of screen sizes dependent on the gradation of the borrow area and required materials. Screening is typically done in the dry, although spray bars may be used to reduce dust. Similar to the raking operation, the larger sizes are separated out first in order to reduce wear on the finer screens.

The final operation is sand washing. Since raking and screening operations separate out the oversize and gravel sizes, only sand, silt, and clay remain at the far end of the plant. Separating the sand and fines (silt and clay) requires wet washing. While a number of methods are commercially available, some proprietary, they consist of the same general concept, introducing the sand/silt/clay mixture into standing water and agitating. This “washing machine” effect permits the larger particles (sand) to go to the bottom of the mixer, while the smaller particles (silt and clay) float to the surface or remain in suspension where they are drained off. The sand is then directed to a conveyor where it is stockpiled, whereas the silty clay slurry is delivered to settling ponds.

In areas where pit run material is not available but high quality rock is, the rock can be excavated by blasting and crushed to sand and gravel sizes. It should not be assumed that the crushed material is free of fines, and material obtained by this

[22] Laboratory gradation testing should always be done using “wet” sieving, while recognizing that the addition of sodium hexametaphosphate (wetting agent) will remove adhered fines—a condition that typically is not duplicated at the processing plant.

method should be washed as described above. Crushing may also be used when insufficient or no sand is present in a borrow area. It should be noted that crushing operations will induce small fractures in the particles, which can result in breakdown during hauling, placing, and compacting operations. Generally, material that is not crushed will have better durability than material that is. Also, material that is crushed will have sharper edges and be less likely to collapse than material that is less angular.

Since the plant separation process results in multiple stockpiles of gravel and multiple stockpiles of sand, these materials are blended back together to make the desired end product. The process, also known as reassembly, is typically a separate operation from the screening plant.

As described in previous sections, lead time to develop a borrow area and process the material can be long. To help offset some of this time, a "materials" solicitation can be produced prior to the solicitation for the major work. A "materials" solicitation can be produced relatively quickly, and a contractor can produce and stockpile material during preparation of the major work specification. This solicitation process can reduce the total project schedule by months. It also helps to minimize risk to the prime contractor because the uncertainty of producing the material has been eliminated for that portion of the work.

5.7.2 Commercially Available Products

In lieu of complete filter design, experience has shown that a modification to fine concrete aggregate, as designated in ASTM C33, meets the design requirements for many base soils. This material is commonly referred to as "C33 concrete sand" or, more simply, "concrete sand." The additional requirement on the No. 200 sieve is needed to meet the permeability requirement of the filter design procedure. Table 5.7.2-1 gives an acceptable gradation band for this material. Because conditions differ from site to site, this gradation specification should always be checked against the base soil.

In a similar manner, when modified C33 concrete sand is used as a filter (first stage), standard materials can be used as the gravel drain or second stage. Several materials in ASTM D448 have been checked against modified C33 concrete sand and are included in table 5.7.2-2. When using modified C33 concrete sand, the D448 materials do not have to be checked because the gradation range of the first stage is fixed. Three materials have been included because not all materials will be available in all areas.

Many State highway agencies also offer standard materials that may be acceptable in filter or drain applications. Each would have to be checked on an individual basis to ensure that they meet the gradation design criteria. Also, aggregate suppliers may produce a material for another customer or application that meets the design criteria.

Table 5.7.2-1. Modified gradation of ASTM C33 fine aggregate[1]

Sieve size	Percent passing, by weight
3/8-inch	100
No. 4	95-100
No. 8	80-100
No. 16	50-85
No. 30	25-60
No. 50	5-30
No. 100	0-10
No. 200	0-2[2]

[1] Requirement beyond the ASTM C33 designation.
[2] Two percent (or less) in stockpile, 5 percent (or less) in-place.

Table 5.7.2-2. Gradation for ASTM D448 drain materials (percent passing, by weight)

Sieve size	Blend 579[1]	No. 8	No. 89
2 inches	—	—	—
1½ inches	100	—	—
1 inch	90-100	—	—
¾ inch	75-85	—	—
½ inch	—	100	100
3/8 inch	45-60	85-100	90-100
No. 4	20-35	10-30	20-55
No. 8	5-15	0-10	5-30
No. 16	0-5	0-5	0-10
No. 50	—	—	0-5

[1] This gradation is a blend, in equal parts, of gradation Nos. 5, 7, and 9. It is not an ASTM standard aggregate.

Second stage gradations can be coarser than those shown in table 5.7.2-2. Table 5.7.2-2 is based on:

$$D_{15}E \leq 4 * D_{85}F$$

where $D_{85}F$ is taken from the concrete sand.

A less stringent particle retention requirement might be used for second stage gradations since the base soil (concrete sand) is a manufactured product and somewhat broadly graded (fine to coarse sand).

In general practice, 5 * $D_{85}F$ has been used in this application. For application where a large amount of seepage is expected (highly pervious foundations), the following relationship can be used, but with caution since it essentially eliminates the factor of safety against particle movement.

$$D_{15}E \leq 9 * D_{85}F$$

Using this relationship, commercially available products have been identified and are presented in table 5.7.2-3.

Table 5.7.2-3. Gradation for ASTM D448 drain materials (percent passing, by weight)

Sieve size	No. 467	No. 57	No. 67
	$D_{15}E \leq 9 \times D_{85}F$		
2 inches	100	-	-
1½ inches	95-100	100	-
1 inch	-	95-100	100
¾ inch	35-70	-	90-100
½ inch	-	26-60	-
⅜ inch	10-30	-	20-55
No. 4	0-5	0-10	0-10
No. 8	-	0-5	0-5
No. 16	-	-	-
No. 50	-	-	-

Based on the D_{50} size of the materials presented in tables 5.7.2-2 and 5.7.2-3, the maximum performation size can be calculated as described in section 5.5.2. Table 5.7.2-4 summarizes the resulting perforation sizes.

Table 5.7.2-4. Maximum perforation dimension for ASTM D448 drain materials, inches (mm)*

No. 467	No. 57	No. 67	Blend 579	No. 8	No. 89
0.53 (13.4)	0.38 (9.6)	0.35 (9.0)	0.37 (9.5)	0.19 (4.8)	0.18 (4.5)

[1] The minimum measurement should be used. For circular perforations, use the diameter; for slots, the width measurement is used.

5.7.3 Costs

Whether or not to develop a local or onsite borrow area is a function of cost and schedule. Cost comparison studies can be done to estimate the unit cost of the material from each site. All other things being equal, the cost to set up and operate a local processing plant is compared against the cost to haul the material to the site from a commercial borrow area. Studies during the Keechelus Dam modification in 2002 indicated that this break-even point is about 20 miles, although there are a number of factors that will have an impact on this distance. Once the cost estimates are made, and if they are found to be significantly different, a decision can be made on which source to use. If the costs are about the same, both developed and commercial schemes may be included in the solicitation. In this way, the most economical scheme will be used for the project.

Consideration should also be given to the project schedule. Depending on land ownership and State regulation, a newly opened borrow pit may require one or more permits. The permitting process can be lengthy (over 1 year) and may not be achievable within the project schedule. There will also be a cost associated with this work, which should be included in the analysis described above.

Typically, the lower the allowable fines content of filter material, the greater the cost. This is due to the amount of processing needed to remove the fines. Washing is usually required to remove the fines, and this operation is one of the most expensive procedures in the production of clean material. Also, more uniformly graded filters are usually more costly than broadly graded filters. As described in section 5.2.4, the amount of gradation uniformity depends on intended use of the filter.

5.8 Construction Considerations

The following sections address construction considerations for a wide range of issues related to their construction including minimum dimensions, lift placement, hauling and spreading, and compaction. The section also describes methods that can be used to limit segregation and contamination and to minimize breakdown. Quality control, inspection, and field tests are also described.

5.8.1 Minimum Dimensions

Chimneys are inclined or vertical protective elements typically situated near the center of the embankment. The chimney connects to the blanket, described below, and as a minimum should extend above the top of active storage. Discharge capabilities of any filter-drain system should be verified by suitable calculations (as shown in appendix A) and/or laboratory tests to ensure that they are capable of removing all water that reaches them without excessive head buildup, clogging, or internal erosion of the filter itself [8].

Three factors influence the width of vertical or inclined filters:

1. **Orientation of the filter** – vertical or inclined.
2. **Loading condition** – static or seismic.
3. **Ability to sustain a crack** – thinner chimneys have a higher likelihood of sustaining a through crack.

Filter width is defined as the horizontal measurement across the filter. The filter thickness is defined as the measurement normal to the slope. Both definitions are illustrated in figure 5.8.1-1. For vertical filters, the thickness equals the width.

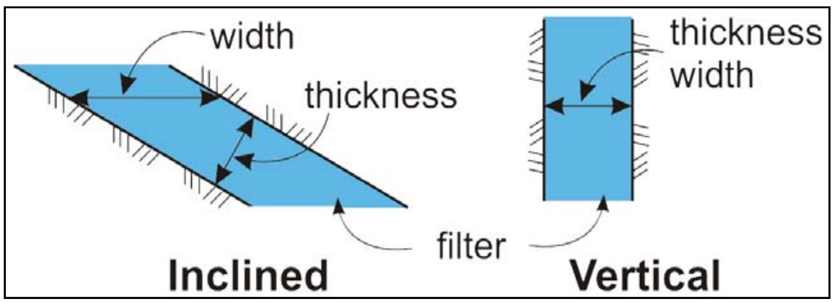

Figure 5.8.1-1. Definition of filter width and thickness.

When filters are placed against a slope, the width is always greater than the thickness. The difference between width and thickness increases as the slope becomes flatter, as shown in figure 5.8.1-2. Due to the "Christmas tree" effect described later, narrow widths on flat slopes can lead to small thickness and even windows, which can be problematic

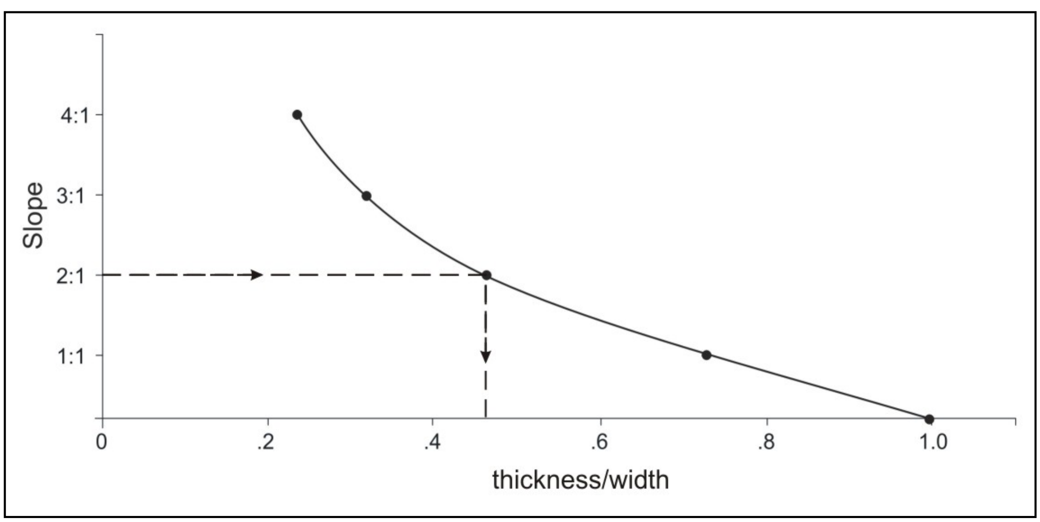

Figure 5.8.1-2. Effect of slope on filter width.

As an example, a 10-foot-wide filter is proposed for placement on a 2:1 slope and the filter thickness needs to be determined. By using figure 5.8.1-2, the following calculations are made and illustrated on the figure:

0.45 = thickness/width for a 2:1 slope
width = 10 feet
thickness = 0.45 * 10 = 4.5 feet

Therefore, this placement will result in a 4.5-foot-thick filter.

When a filter is being designed to address seismic issues, the size of the filter is generally controlled by the maximum deformation expected from the seismic event. Deformations come from foundation fault displacement, foundation or embankment liquefaction, slope failure, and nonliquefaction settlement of the embankment or foundation. As an initial rule of thumb, the filter size should be at least twice as large as the expected deformation (horizontal or vertical) in order to provide an adequate factor of safety.

When seismic protection is not required, filter width is typically controlled by construction methods. Since a variety of equipment is used for hauling and placement, and the size of that equipment is related to the size of the job, a variety of filter widths are found to be acceptable. Proven methods indicate that inclined chimneys can be reliably constructed at 6-foot and wider widths [7], and vertical filters can be reliably constructed at 4-foot and wider widths. Surveying and quality control/quality assurance are critical to ensure filter continuity, and the intensity of these requirements increases as filter width/thickness decreases.

Narrow zones require special placement procedures and intense inspection during construction. The crack resisting/self-healing capabilities of narrow zones are also less than for wide zones, and they should not be used if adequate materials are economically available. Often, reduced placement costs of wider zones will offset increased material quantity when narrow zones are contemplated. Cost considerations should only be the deciding factor when narrow zones meet the design requirements (hydraulic capacity, crack stopping, filtering, accommodation of postulated seismic movement, and self-healing) adequately. Narrower filters can also become too thin when placed on flat slopes. Table 5.8.1-1 summarizes the filter thickness for a range of slopes and highlights filter width/slope combinations that result in a thickness of less than 2 feet [55].

Table 5.8.1-1. Normal thickness of inclined chimney filters. Shaded cells indicate filter thickness less than 2 feet

Slope	Width – feet				
	16	**9**	**6**	**5**	**3**
1:1	11.7	6.6	4.4	3.6	2.2
2:1	7.5	4.2	2.8	2.3	1.4
3:1	5.1	2.9	1.9	1.6	1.0
4:1	3.8	2.2	1.4	1.2	0.7

When narrow inclined zones are used, the designer should realize that placement procedures do not result in straight interfaces between filter drains and surrounding zones, but many have more of a "Christmas tree" appearance as shown in figure 5.8.1-3. While this photograph illustrates an overbuild condition, a more common underbuild condition is also possible. When underbuilt, the filter necks down and, in the most extreme cases, is nonexistent, leaving an unprotected window in the filter. The specified minimum width should account for the "Christmas tree" configuration to ensure adequate drainage capacity.

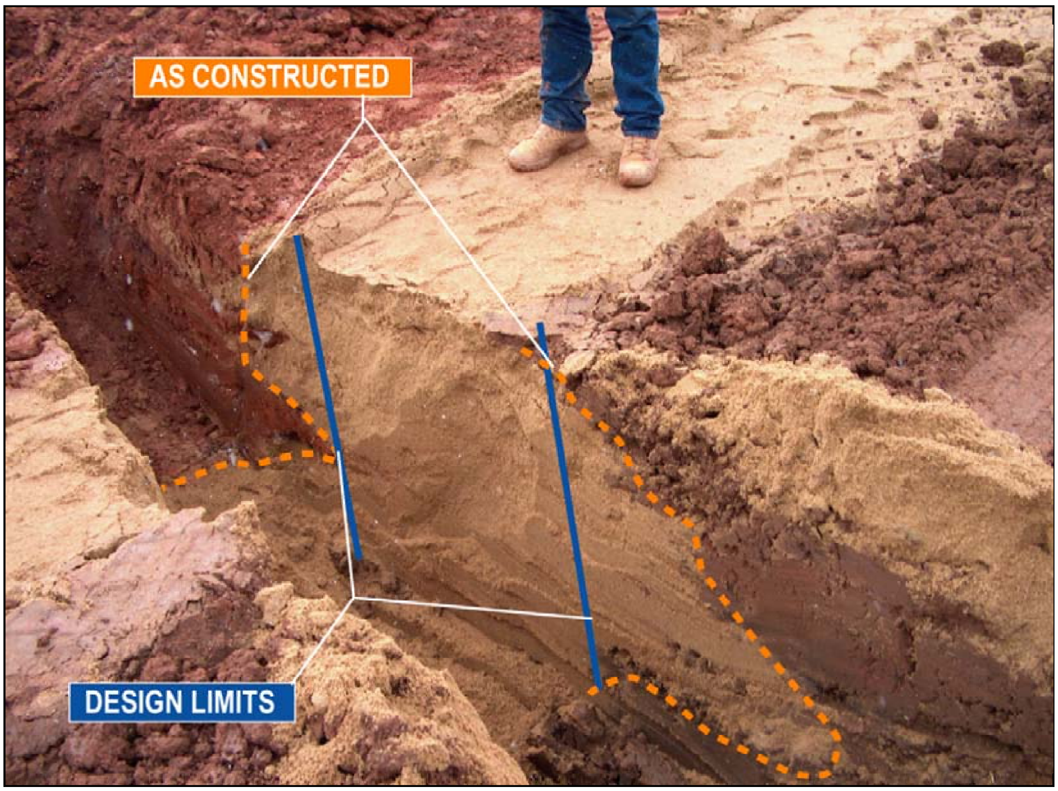

Figure 5.8.1-3. "Christmas tree" effect in a sloping chimney filter. (Photo courtesy of URS Corp.)

Inclined chimneys also experience a reduction in width when lifts are not placed at a uniform elevation along the direction parallel to the axis of the dam. As the chimney is brought up, it is possible, and usually likely, that there will be low spots, or sags, along the top of the chimney. When a low area exists, a common mistake is to continue the lower portion parallel to the axis of the dam when that portion should actually shift downstream, and failing to make this correction will result in the chimney "thinning" out in the area of the sag. For a 2-foot sag on a 3H:1V (horizontal:vertical) slope, this can result in a 6-foot error. This error can also result in the filter pinching out or leaving a window in the filter.

5.8.2 Chimney Construction

Three basic construction methods can be used to construct vertical and inclined sand filter/drains and transition zones in embankment dams [56]:

1. Maintain the adjacent impervious core one lift ahead of the sand filter/drain.
2. Maintain the sand filter/drain one lift ahead of the impervious core.
3. Trenching.

5.8.2.1 Maintain Adjacent Core One Lift Ahead of Filter

While this method is not recommended for most applications, it is included for reference as a historical procedure. Figure 5.8.2.1-1 shows steps used in this method of construction. This technique has the advantage of minimizing spreading of sand material during compaction and could facilitate in obtaining the desired or specified percent compaction or relative density. However, this method is more conducive to contamination of the sand filter/drain by adjacent materials falling into the section and from material being washed in during rains or by the spray from a passing water truck. Another disadvantage of this method is the difficulty in maintaining a specified filter width. Since adjacent materials are placed and compacted first (i.e., above the filter), there is a tendency for these materials to overlap into the sand filter/drain zone.

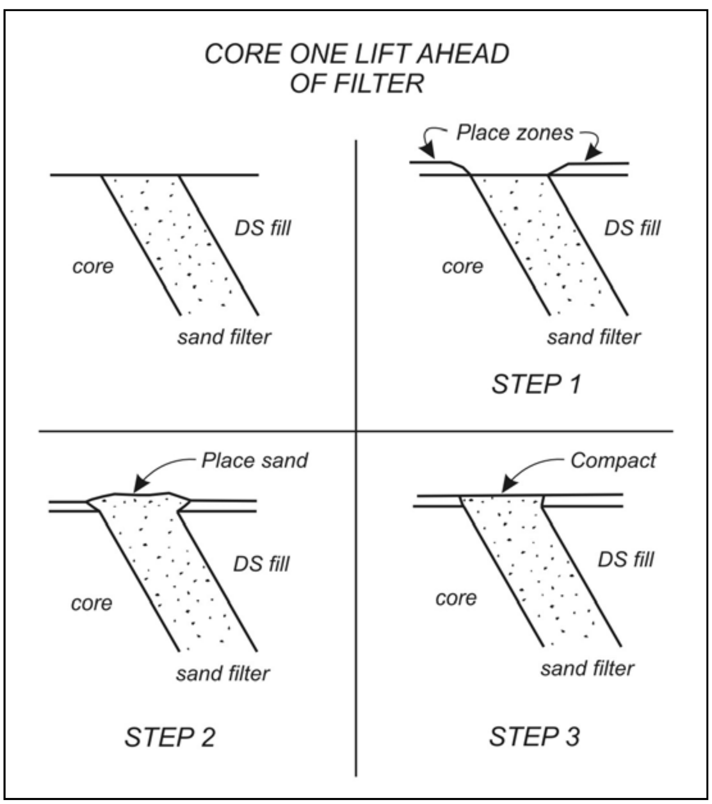

Figure 5.8.2.1-1. Steps in maintaining impervious core one lift ahead of a chimney (not recommended).

5.8.2.2 Maintain Filter One Lift Ahead of Core

Figure 5.8.2.2-1 shows the sequence of construction for this method. This method has the advantage of helping prevent contamination and maintaining vertical continuity and full width of the filter/drain. This is especially true if the embankment surface is maintained so that the filter/drain is the high point of the cross section, resulting in runoff and potential contaminants flowing away from the filter/drain zone. A disadvantage of this method is that compaction may be more difficult because the sand has a tendency to spread at its outer edges when compacted. Spreading also may result in a greater quantity of filter/drain material being used to construct the required width. This could result in a significant increase in cost because the filter/drain is often the most expensive material in the embankment. However, experience has shown that these disadvantages may be significantly overcome by blading up a windrow of loose material at the edge(s) of the filter/drain as shown in figures 5.8.2.2-1 and 5.8.2.2-2. The windrow should be of sufficient width to effectively contain the filter/drain material, thereby minimizing spreading during compaction. Although this method may result in using additional filter/drain material due to a small "Christmas tree" effect, the extra cost is a small price to pay for ensuring that the drain width and gradation are constructed as designed. This method is especially applicable to filters/drains having a relatively narrow width.

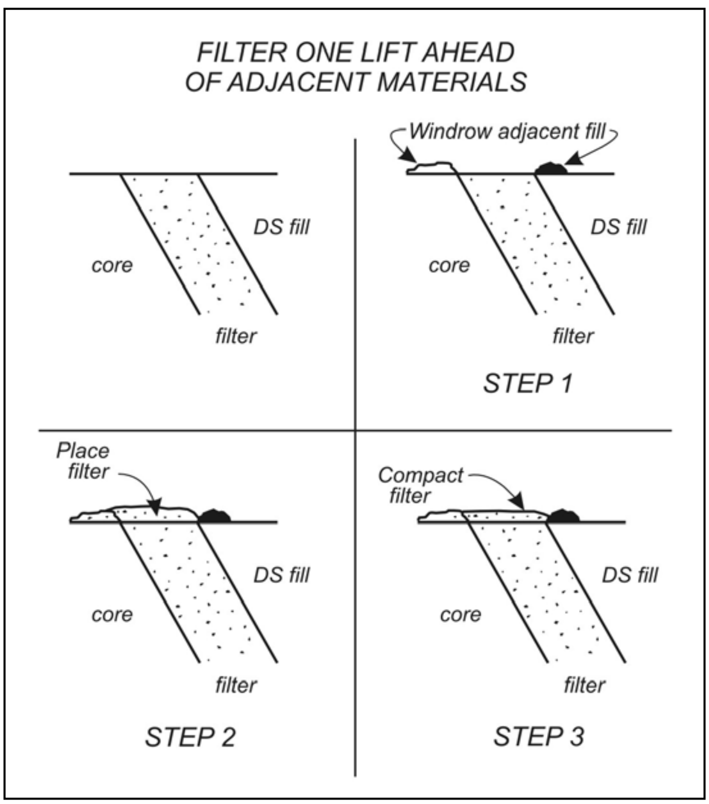

Figure 5.8.2.2-1. Steps in maintaining a chimney one lift ahead of impervious core.

Figure 5.8.2.2-2. Windrowing impervious material adjacent to a filter/drain.

5.8.2.3 Trenching

The trenching method is shown in figures 5.8.2.3-1, 5.8.2.3-2, and 5.8.2.3-3 and is utilized when the filter/drain is constructed within a basically homogeneous impervious core. In this method, the impervious core is built completely over the filter/drain for a thickness of 3 to 5 feet. Using a trenching machine or other suitable excavation equipment, the core is then excavated down to the top of the previously completed filter/drain, and the trench is backfilled with compacted filter/drain material. The trenching method facilitates compaction since the material is confined on three sides, provides for closer control of quantities, and is conducive to obtaining excellent contacts between the filter/drain and adjoining impervious core. Disadvantages include the fact that trenching is time consuming, expensive, inspection intensive (to ensure the tie-in between the existing filter/drain material and the newly placed material is not contaminated), and arching may occur across the trench reducing the ability of the filter to self heal. In addition, this method can be used only for construction of narrow, vertical filter/drains in embankments composed of central and downstream homogeneous material that will stand vertically without caving when trenched.

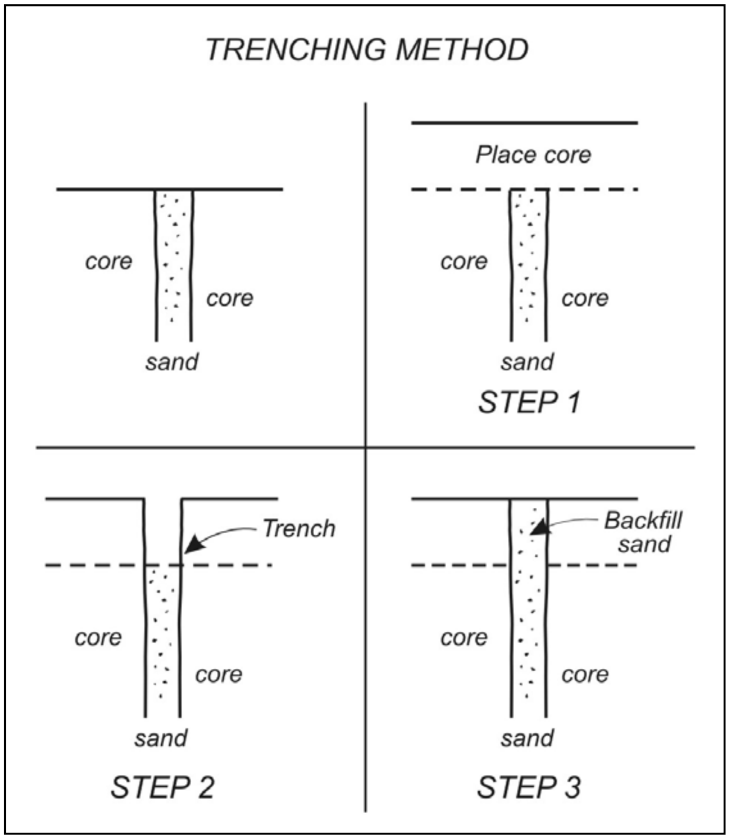

Figure 5.8.2.3-1. Steps for trenching method.

Figure 5.8.2.3-2. Trenching method – excavating trench.

Figure 5.8.2.3-3. Trenching method – backfilling trench.

5.8.2.4 Hauling and Dumping

The hauling and dumping process can contribute to segregation and contamination of filter/drain material if not carefully monitored to ensure that the methods employed will minimize detrimental effects. Normally, trucks are used for hauling filter/drain materials. On large jobs, either off-road large-end dump trucks (sometimes referred to as quarry trucks) as shown in figure 5.8.2.4-1, or articulated trucks that can be end-, side-, or bottom-dump are used. Figure 5.8.2.4-2 shows an articulated bottom-dump used to deliver filter and drain materials. On smaller jobs, over-the-road end-dump trucks may be employed. Regardless of the type used, because of the possibility of contamination, tracking of hauling equipment on the filter/drain either must be prohibited or, if unavoidable, kept to the minimum necessary. If traversing the filter/drain material cannot be avoided during the dumping process, operators should be instructed that once they are on the filter/drain material, they should stay on because moving off and on again can increase the chance of transporting adjacent materials to the filter/drain, thereby causing contamination. Insofar as practical, material should be dumped as close to the required loose lift thickness as possible. Authorized crossing points should be established for all construction equipment (including pickup trucks) that must cross the filter/drain. If bottom-dump equipment is used and zone width allows, trucks should straddle the filter/drain material for discharge and use authorized crossing points for entrance and exit. Side-dump equipment is good for dumping filter/drain materials because it normally does not have to traverse the filter/drain. End-dump trucks are the most commonly used type of hauling equipment and should dump perpendicular to the longitudinal axis of the filter/drain to minimize tracking. This may require extra positioning to avoid dumping the entire load in one place (which often will require additional blading to properly spread the material). If the wheel base is wide enough, trucks should straddle the filter/drain for dumping. Equipment used for transport of filter/drain material may be earmarked for that purpose exclusively and not be used for other work. Truck boxes (beds) should be inspected regularly as the work proceeds because pockets of fine materials have a tendency to become concentrated in corners and may be released during dumping. All filter/drain areas traversed by equipment must be inspected and any deleterious material deposited from the tire treads removed. This requires constant attention and often may require hand work.

Figure 5.8.2.4-1. Large end-dump truck using an equipment crossing over a chimney filter.

Figure 5.8.2.4-2. Articulated bottom-dump truck. The photo illustrates difficulty that can arise when the truck dumps too quickly for the speed of the truck. The trailer will then hang up and require assistance from other equipment.

5.8.2.5 Spreading

Chimney filters and drains can be spread out using a number of methods which are typically dependent on the width of the filter. For chimneys 8 feet and wider, direct delivery by truck and blading by dozer or grader are used. For narrower chimneys, spreader boxes or truck mounted conveyors are used. Details of these methods are presented in the following sections.

5.8.2.5.1 Blading

Since spreading dumped material by blading inherently causes segregation and possibly contamination, blading should be kept to a minimum. Blading is usually accomplished by graders or dozers as shown in figure 5.8.2.5.1-1, with tracking off the filter kept to a minimum to lessen the chances of contamination. To minimize segregation, spreading equipment should be operated at minimum speeds and tracking on the filter minimized. Some hand work may be required in addition to blading.

Figure 5.8.2.5.1-1. Spreading sand filter material.

5.8.2.5.2 Spreader Box

A spreader box can also be used for spreading sand filter/drain material as shown in figure 5.8.2.5.2-1. Material is dumped into the spreader box bin, which is then pulled or pushed (depending on the particular operation) along the axis of the filter/drain zone. As the spreader box moves, material feeds out the rear of the box, releasing material at the specified loose lift thickness and width. Use of this device can be somewhat cumbersome, but it is usually worth the extra effort because no blading or trafficking by equipment (other than by the prime mover for the box) is required to place the filter/drain material in the exact loose lift thickness and zone width. Several variations of spreader boxes have been used, each being constructed to fit specific project requirements. At another project, the box was configured with a divider wall to place both the first and second stages simultaneously as shown in figure 5.8.2.5.2-2. Each zone was 4 feet wide and was placed in a 12-inch loose thickness. The box was filled with material from either side, as shown in figure 5.8.2.5.2-3, and towed by a Caterpillar D-6 dozer at a slow speed as shown in figure 5.8.2.5.2-4. In another case, the spreader box shown in figure 5.8.2.5.2-5 placed two 5-foot-wide zones simultaneously but was fitted on the front of a dozer with hydraulic lift capabilities. Both materials flowed out of the box at the proper zone width and loose lift thickness as the dozer operated in reverse as shown in figure 5.8.2.5.2-6. Mobility of this type spreader box is significantly increased over that of a towed unit.

Figure 5.8.2.5.2-1. Basic single-bin spreader box.

Figure 5.8.2.5.2-2. Double-bin spreader box.

Figure 5.8.2.5.2-3. Dumping into spreader box.

Figure 5.8.2.5.2-4. Towing spreader box.

Figure 5.8.2.5.2-5. Double-bin spreader box fitted to dozer (side view).

Figure 5.8.2.5.2-6. Double-bin spreader box fitted to dozer (end view).

5.8.2.6 Truck-Mounted Conveyors

Beginning in 2000, contractors began using trucks outfitted with a conveyor for use in the placement of narrow width filters and difficult to access site conditions. The trucks, originally intended to deliver grain for agricultural applications, were modified to handle granular soils. The truck consists of a large box or hopper similar to a dump truck that holds the material and a conveyor mounted to the rear of the vehicle. The conveyor can both swing relative to the long axis of the truck and can be raised and lowered. This mobility is similar to that seen for the chute in concrete delivery trucks. Some trucks can be remotely operated using controls at the end of a long control cable, allowing the driver to place material without assistance. Material is then delivered to the zone in a fashion similar to concrete placement. When care is taken, the material can be uniformly placed to the desired lift thickness, and no leveling is required. When less skilled operators are used, some raking by hand may be required, but spreading by a dozer is seldom needed. Figure 5.8.2.6-1 illustrates this operation in the construction of a 4-foot-wide chimney filter being added to an existing dam.

Figure 5.8.2.6-1. Truck conveyor delivering filter sand for the addition of a 4-foot-wide chimney filter to an existing embankment. Note that the material is uniformly placed from the conveyor, and no leveling is required. Dynamic compaction is provided by the roller shown in the foreground.

5.8.3 Segregation

Completely eliminating segregation during construction is practically impossible because the material must be handled, and handling itself will cause some amount of segregation. However, adhering to proper construction practices that have been established by experience for storing, hauling, dumping, spreading, and compacting filter/drain materials can significantly reduce the amount of segregation [57].

Segregation during processing and placement is a common problem. Segregation may result in overly coarse filter/drain materials in contact with adjacent finer materials, which would negate the effect of the filter. Incompatibility at the interface materials would be the result. Many investigators consider segregation control during construction as the most important aspect of constructing a filter/drain. Segregation can have a significant bearing on the ultimate performance of the embankment dam.

A common cause of segregation is the manner in which material is handled. Material placed in a pile off a conveyor, or loaded from a chute, or from a hopper segregates because the larger particles roll to the sides of stockpiles or piles within the hauling unit. Material dumped from a truck, front loader, or other placing equipment almost always segregates, with the severity of the segregation corresponding to the height of the drop. When material is dumped on the fill, segregation occurs.

Segregation can be adequately controlled in several ways. First, the designer can specify a uniformly graded filter or drain and limit the maximum sizes as discussed earlier in this design standard. Secondly, construction techniques to control segregation should be specified and enforced. Use of rock ladders, spreader boxes, and “elephant trunks” for loading hauling units, and hand working the placed materials, help prevent segregation. If material is dumped, limiting the height of drop to less than 2 feet helps. Placing filter/drain material with belly dumps sometimes adequately limits segregation during placement. Limiting the width of the belly dump opening by chaining or other means can increase its ability to limit segregation. Using baffles in spreader boxes and other placing equipment can help reduce segregation. The personnel inspecting the filter/drain production, placement, and compaction should be apprised of the importance of limiting segregation.

5.8.3.1 Front-to-Back Segregation

Front-to-back or belt segregation typically occurs on conveyor belts where fines vibrate to the bottom and coarse particles remain on the top as the material bounces across the idlers (figure 5.8.3.1-1). Additionally, at the end of conveyors, if left undeflected, coarse particles are thrown out and away, while the fine particles tend to drop down and, possibly, under the end of conveyor. The greater the speed of the belt and drop height, the worse the particle segregation. This segregation can be lessened by slowing belt speed, minimizing drop height, and using baffles. Other mechanical changes can be made to the conveying system that will also help prevent segregation. These alterations are described in “Inspection and Sampling Procedures for Fine and Coarse Aggregate” [58].

5.8.3.2 Roll-Down Segregation

Segregation can also occur while creating stockpiles, with segregation becoming worse as the pile height increases. Larger particles then roll down the side slope of the pile as shown in figure 5.8.3.2-1. The higher the pile and greater the drop height, the worse the problem. Segregation from this operation can be significantly lessened by limiting drop and stockpile heights.

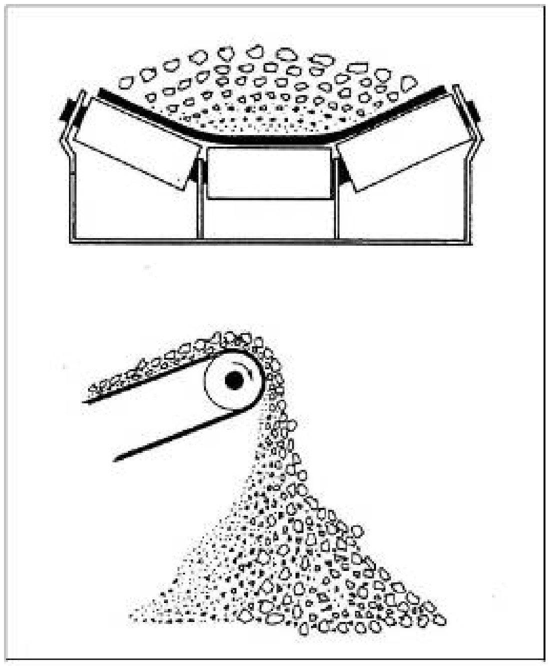

Figure 5.8.3.1-1. Front-to-back or belt segregation.

Figure 5.8.3.2-1. Segregation at high stockpile of broadly graded material. This photograph is an example of roll down segregation, and the shown material would not be acceptable for use as a filter (photo courtesy of A. Breitenbach).

5.8.4 Particle Breakage

All granular materials experience breakage during placement and compaction operations. Typically, loaders, and possibly dozers, place the material in stockpiles from which it is loaded into trucks, dumped onto the fill, bladed to a uniform loose lift thickness, and compacted by a smooth-drum roller. Each of these operations can cause individual particles to break down. This breakage is aggravated in crushed aggregates. This breakage leads to a change in gradation between what is produced at the plant and what is in place in the embankment. Reclamation has monitored breakage between the source and the in-place fill on construction projects for the past 40 years by performing gradations at both points. Results of these gradations indicate that particle breakage typically results in an increase in fines of between 1 and 3 percent, with 2 percent being typical for materials in the Western United States. It should be noted that, generally, material from a crushing operation will experience greater breakdown than processed pit-run. Based on these data, gradations produced at the source should be 3 percent less than that desired in the embankment. When specifying material gradations at the processing plant, particle breakage should be taken into account and gradation tests run on in-place material. When material gradation is specified only for the fill, it will be the contractor's responsibility to address breakage between the plant and the fill. This situation can lead to delays and, possibly, claims by an inexperienced contractor.

For small projects, it may not be practical to determine aggregate quality by laboratory testing. In this instance, the designer should consider the mineralogy of the parent material. Quartz-based aggregates have higher quality than aggregates that come from sedimentary rocks. For materials obtained from commercial sources, stockpiles should be examined for slope uniformity. Piles with irregular or near-vertical slopes may indicate high fines content or, possibly, the presence of binders or cementing agents in the material similar to what is seen in figure 5.8.4-1.

Figure 5.8.4-1. Sand and gravel stockpile (recycled concrete) that indicates fines or binding agents are present due to verticality and overhang seen in the slope.

5.8.5 Compaction

Filter zones are usually compacted for one or more of the following reasons:

- So they will not settle excessively on wetting.
- So they will not liquefy when loaded dynamically.
- So that a design shear strength will be achieved.
- To aid in obtaining strain compatibility with adjacent zones in the dam.
- Particle retention criterion is based on compacted material.

These characteristics normally require a relatively high density. On the other hand, there are valid reasons why sand filters/drains and transition zones should not be compacted to an excessively high density.[23] Very densely compacted sands can result in overly brittle zones that have less than desirable self-healing properties (sustain a crack). Requiring a high shear strength and low compressibility always has the accompanying properties of a more brittle zone with a tendency to crack upon deformation and to arch in narrower zones. In order to achieve high densities, several passes of a heavy vibratory roller are sometimes specified. This has a tendency to increase the potential of particle breakage that can produce a thin layer of excessive fines at the lift surface, which can have the effect of reducing vertical permeability, while at the same time reducing self-healing properties of the material.

Fundamentally, compaction of granular soil is accomplished by applying energy to the soil mass through the use of a roller. The amount of energy applied by the roller is a function of its weight, dynamic force, the number of passes it makes over a given area, and the lift thickness. These factors can be varied in many different ways to achieve the required density but are reduced by the desire to minimize particle breakdown. In order to minimize breakdown, the number of passes should not be more than two, and the number of lifts should be kept to a minimum so that the number of lift interfaces is kept as small as possible. The following sections will describe typical compaction methods that will achieve these requirements.

5.8.5.1 Field Compaction

The most effective types of equipment for compacting clean granular materials are those that employ vibration such as vibratory rollers or vibratory plate compactors. Vibratory rollers have a long and successful history in compacting clean sands like those used in filter/drain zones. D'Appolonia et al. [60] reported good compaction for ASTM C33 clean sand using a relatively small (12,500-pound) roller. That research concluded that compacting relatively thin lifts (less than 1.5 feet) with about two passes of a lightweight vibratory roller obtained good compaction results, which equaled about 75-percent relative density for the sand evaluated.

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[23] "Compaction of filters should be minimal. Excessive compaction, particularly of crushed rock, can lead to the creation of sufficient fines in the filter to make them susceptible to cracking." [59]

Thoroughly wetting sand prior to compaction has often been recommended but is not required. Dynamic loading by the compactor is the critical component in compacting granular materials.

5.8.5.1.1 Vibratory Compactors

Vibratory compactors or "rollers" range in size from large double-drum types to smaller "walk-behind" drum or plate models. Examples of these type rollers are shown in figure 5.8.2.6-1 and figures 5.8.5.1.1-1 through 5.8.5.1.1-3. Specifications normally require one or more of the following characteristics when "method specifications" are used in a contract:

- Static weight
- Drum diameter and width
- Range of operational frequencies of vibration
- Imparted dynamic force
- Roller operation (covered in following section)

All specified static and dynamic properties of the particular roller must be checked and verified to be in accordance with the specification requirements prior to use. A test fill, prior to beginning construction of a filter or drain, is usually specified to ensure that the compactor will satisfactorily obtain the required results, even when the compactor characteristics have been specified.

Figure 5.8.5.1.1-1. Double-drum vibratory roller.

Figure 5.8.5.1.1-2. Single-drum vibratory roller.

Figure 5.8.5.1.1-3. Walk-behind vibratory plate compactor.

5.8.5.1.2 Compactor Operation

Operation of the approved roller will be specified in terms of number of passes, overlap between passes, maximum speed of operation, and operating frequency. In addition, there may be additional operating requirements relating to turning and backing. The roller must be in motion when the dynamic force is engaged or disengaged. Also, the roller should not be permitted to sit idle with the dynamics engaged because this will lead to “digging-in” and overdensification of the filter. The number of roller passes on each lift, as well as roller overlap (usually a minimum of 1 foot), must be verified by field observation. A roller pass of a smooth-drum vibratory roller is defined as a complete coverage of the area to be compacted with each trip of the roller. One pass of a double-drum roller[24] is normally equivalent to two passes of a single-drum roller. Since these terms are subject to interpretation, these definitions should always be included in the specification. Roller speed can be readily checked by timing the movement of the roller over a known distance until the inspector is comfortable in visually assessing the speed.

5.8.5.1.3 Compaction Along Conduits

Compaction along conduits requires special consideration due to poor compaction methods used in the past related to seepage collars. Consideration also needs to be given to the strength of reinforced concrete conduits at the time of compaction. For new conduits sufficient time needs to be allowed so sufficient concrete strength is achieved to withstand the compaction. Compaction requirements should not be lessened in order to place fill shortly after the concrete pour or to correct for issues in the construction schedule.

Compaction adjacent to conduits should be parallel to the conduit, i.e. transverse to the axis of the dam. Note that this is opposite of the direction, i.e. longitudinal to the dam axis, used for chimney filters. Fill should be placed equally on each side of the conduit sloping away from the structure as shown in figure 5.8.5.1.3-1. Also as shown in the figure, the tires or drum of the compactor should run against the conduit face. That is, there should not be an offset between the conduit and compactor and 'zone of special compaction' should not be used.

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[24] Assuming that dynamic force is applied to each drum.

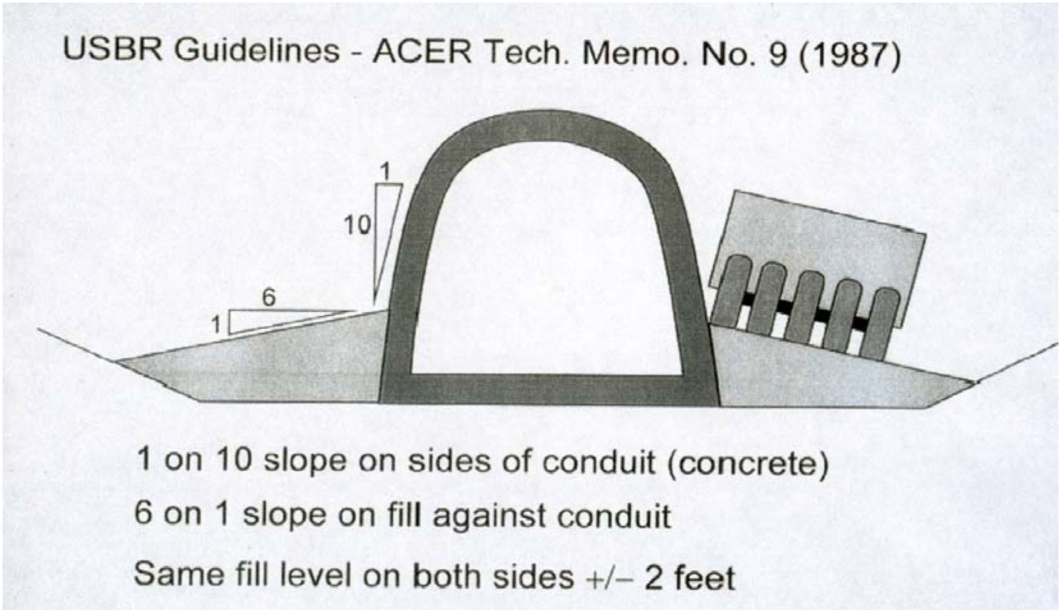

Figure 5.8.5.1.3-1. Recommended fill placement and compaction adjacent of a conduit.

5.8.5.1.4 Compaction of Contacts Between Zones

Contacts between the filter/drain and adjacent materials, such as between the filter/drain and the impervious core, must be adequately compacted. If left uncompacted, an area of low shear strength and high compressibility could develop along the contact. Compaction of zonal contacts can be overlooked rather easily since the filter/drain is compacted by smooth-drum vibratory rollers and the impervious core is normally compacted by a tamping (sheepsfoot) or a rubber-tired (pneumatic) type roller. Equipment operators of each type of roller are often given instructions to avoid tracking on adjacent zones. Each operator working in accordance with his instructions may result in the area around the contacts not receiving adequate compaction.

Proper compaction of the contacts is accomplished by overlapping the vibratory roller onto the adjacent material rather than overlapping the tamping roller onto the filter/drain. However, roller operators and inspectors should be taught that a minor amount of mixing of the two adjacent materials is less a detriment than leaving the contact uncompacted. An overlap of 1 foot is usually specified. To facilitate compaction of contacts, all grade stakes used to mark zonal contacts prior to compaction should be removed so that operators do not drive around the stakes. Density testing should be conducted at or near zonal boundaries to verify that adequate compaction is being achieved in these critical areas. An example of rolling a sand filter/drain contact is shown in figure 5.8.5.1.4-1 [56].

Figure 5.8.5.1.4-1. Compacting a joint between two zones by a vibratory roller. Note that the use of spray bars is no longer recommended.

5.8.5.1.5 Compaction Requirements

Compaction of filter and drain materials should be adequate to produce sufficient density to preclude liquefaction, limit consolidation, and provide adequate strength. However, excess compactive effort can cause particle breakdown and reduce permeability (section 5.8.4). Therefore, the amount of compactive effort should be limited to that required to produce the required strength and consolidation without causing excess particle breakage and unnecessarily high densities, which both reduce permeability. Consideration should be given to the number of passes specified instead of just using what has been used previously. If two passes will result in the required density, then additional passes are not justified because they will reduce permeability by causing more particle breakdown and increased density. The idea often exists that if two passes are necessary, three are better. This may not be the case, and the contractor and his operators should be aware so that additional passes are not made to ensure no failing densities or to fill in operator slack periods.

The minimum density should generally not generally be less than 70-percent relative density, particularly if liquefaction is a concern. Whenever in-place grain-size limits for filters/drains are specified, the grain-size tests should be made on samples taken from in-place fill after compaction. Ring permeability tests made at various levels in test fills are one way to obtain realistic permeabilities representing vertical permeabilities of compacted filters and drains. Laboratory procedures that closely duplicate field placement and compaction methods can also provide reasonable values for expected levels of permeability in filters and drains. If proposed materials do not have sufficient permeability after compaction, changes in grain sizes should be made to provide the required permeability. Also, designers should consider changes in layer thickness or geometries of drains that increase discharge capacity to the required levels, while providing the needed filter protection.

Over compaction of filter material can also results in particle breakdown near the top of the lift which can result in a heterogeneous material. This anisotropy may results in a vertical permeability less than the horizontal permeability which could result in poor performance of chimney filters.

5.8.5.2 Moisture Requirements

Experience has shown that because of the free-draining characteristics of granular materials, saturation to provide maximum density is very difficult to obtain/maintain and is no longer recommended. One method that has been attempted in the past to help accomplish saturation is to attach a spray bar to the roller so that the water is applied just ahead of the roller. A second option is to operate a water truck along with the roller so that the water may be applied manually just ahead of the roller.

However, both of these methods are time consuming, difficult to coordinate, expensive, and yield questionable results. Merely sprinkling the material prior to compaction will only increase the moisture content slightly. When the moisture content of a granular material is somewhere between completely dry and fully saturated, the phenomena of bulking occurs. When granular soils are partially saturated, capillary tension takes place between the soil grains, which works against achieving maximum density. This is shown graphically in figure 5.8.5.2-1 where the lowest density is achieved at modest moisture contents, the opposite of what is seen in a Proctor compaction curve. Fortunately, the capillary forces that develop during bulking can be easily overcome with dynamic energy. The use of vibratory compaction is now recognized as the most effective way of densifying granular materials regardless of their degree of saturation. However, Milligan [61] and others have pointed out that moistened sand tends to segregate significantly less during handling than dry sand. If the sand is completely dry in the stockpile, it should be wetted prior to handling and placement.

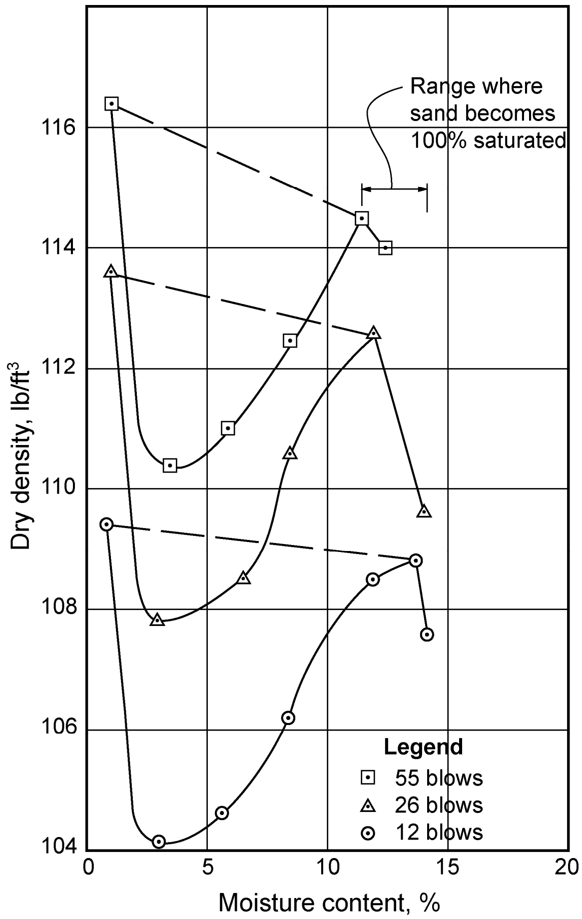

Figure 5.8.5.2-1. Typical compaction curves for a clean sand. Notice that this relationship is the opposite of what is seen in soils that contain fines [62].

5.8.6 Contamination

To avoid contamination of filter/drain zones with excess fines from flanking fill zones during construction, several techniques should be used. The filter/drain zone should be maintained higher than the surrounding fill surface, and the surrounding fill should be placed to maintain drainage of surface water (and sediments) away from the filter/drain zones. This prevents the flow of muddy water into the filter or drain. Traffic should be well controlled, with crossings limited to prepared haul routes that will be removed entirely prior to placing of additional filter/drain materials. Crossings should be staggered to remove any possibility of vertical transmissibility of the filter/drain zone being reduced. Durable materials should be specified, and compactive effort should be held to the minimum necessary to obtain desired in-place density, to minimize particle breakdown during placement and compaction. Equipment for placement and compaction of filter/drain zones should be maintained clean and restricted to operation only on the filter/drain zones; additional equipment should be cleaned before moving onto the filter to avoid unnecessary cross contamination. When the construction season is terminated, the surface of the filter/drain zones should be covered (in addition to surface drainage requirements) and the covering material removed completely before resuming placement in the subsequent season.

Contamination can also occur during loading, hauling, placing, and compaction because these processes tend to cause breakdown of the materials, sometimes to the extent of causing the gradation to be out of specification requirements. Contamination can occur in the stockpile. Dust abatement control procedures and use of equipment around the stockpile that is maintained in a clean condition reduce this problem. It may be necessary to reprocess or not use the bottom foot or so of the stockpile because that is where the greatest contamination of the stockpile generally occurs. Generally, the concern is for an increase in the fines content because these fine materials can reduce the filter permeability. However, breakdown of any particle size can be detrimental since this may alter the ability to filter or be filtered.

The percent fines after compaction should not exceed 5 percent to ensure that permeability is not decreased to an unacceptable degree. To achieve this, the material has to contain less than 2 percent fines in the stockpile, depending on the durability of the particles. Durability requirements should be specified. Durability requirements equal to those used for concrete aggregate are preferred, and they usually ensure that the material can withstand necessary processes to be placed and compacted without excessive breakdown, while also helping ensure long-term durability during project operation. Although it is desirable to make the specifications requirement for filter material gradation in place after compaction, in some instances, such as when material is preprocessed in a prior contract, after-compaction requirements are not practical. In these cases, specifying clean material (less than 2 percent fines in the stockpile) and adequate durability becomes even more important.

Stockpiled materials can become contaminated by airborne dust and drainage runoff, resulting in an increased amount of fines in the material. Dust abatement procedures should be used to prevent contamination by fines into the stockpiled material. Positive drainage should be maintained so that suspended sediment is not carried into the stockpile [57]. A stockpile pad should also be used to minimize contamination between the stockpile and ground surface. Stockpile pads can consist of concrete, geomembrane, or an overexcavation backfilled stockpile material.

5.8.6.1 Protection of Completed Work

The following sections provide guidance on protecting the work from weather and equipment travel. Specifically described are protection from erosion caused by rain and protection from freezing during winter months in cold climates.

5.8.6.1.1 Surface Grade

The surface grade of the embankment should be maintained so that the filter/drain is protected at all times from contamination by surface runoff. To accomplish this, the filter/drain should be maintained at the crown of the embankment surface and protected by whatever means necessary (grading, windrows, etc.) at the end of a shift or when impending storms are forecast. In addition, the embankment surface should not contain low areas, especially those that involve filter/drain zones. Inspectors should watch for contamination resulting from overzealous water truck operators on adjacent zones. Whenever contamination of filter/drains occurs, all contaminated material must be removed prior to resuming normal placement operations. Figure 5.8.6.1-1 shows the damage that can be caused by uncontrolled surface runoff.

Figure 5.8.6.1.1-1. Surface water contamination of a chimney filter.

5.8.6.1.2 Haul Road Crossings

In order to construct a zoned embankment, equipment used to construct other zones must inevitably cross the filter/drain/transition zone as shown in figure 5.8.6.1.2-1. Equipment crossings are fraught with potential for contamination of the filter/drain, for reduction in filter/drain width, and for the filter/drain to be partially or completely cut off vertically. Therefore, special measures must be taken to ensure that the crossings do not adversely affect the design cross section or the desired properties of the filter/drain. Equipment crossings must be controlled; they must be kept to the absolute minimum necessary and must be in definite and confined locations. All personnel working on the dam must be instructed as to crossing locations and the importance of using them.

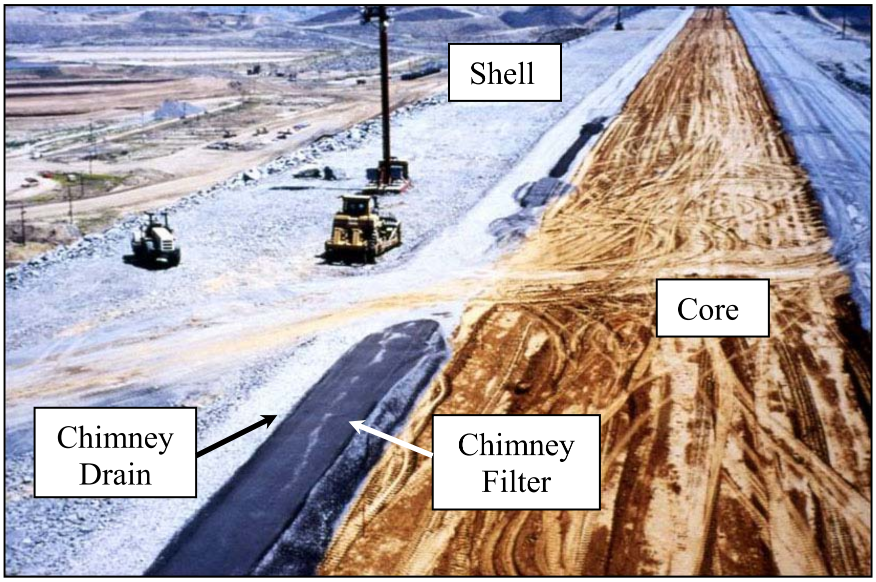

Figure 5.8.6.1.2-1. Haul road crossing of a chimney filter and drain.

Assuming crossings are kept to a minimum and are at specified, confined, and well-marked locations, one method to protect the filter/drain is to place a "sacrificial pad" of drain material at each crossing. This pad should be wide enough to accommodate equipment being used and should have a minimum thickness of 18 inches. When the crossing is no longer needed, the pad and drain material below the crossing are excavated, and the drain is brought back to desired grade with clean, well-compacted filter/drain material. Excavation of a crossing is shown in figure 5.8.6.1.2-2. Another method requires the placement of a heavy geomembrane or steel plates over the drain at the crossing to help protect the material from effects of vehicle traffic. Placement of a geomembrane is shown in figure 5.8.6.1.2-3. Even with the use of a geomembrane or steel plates, some undercutting and backfilling of the filter/drain material will still be required, but usually not to the extent required without the covering. Regardless of the method of protection used, careful visual inspection and gradation test(s) should be performed on in-place material prior to allowing placement of additional filter/drain material. Such inspection and testing would verify and ensure the site's condition, as well as provide a documented record of acceptable crossing cleanup practice.

Figure 5.8.6.1.2-2. Excavation of filter material under equipment crossing.

Figure 5.8.6.1.2-3. Placement of geomembrane at crossing over a chimney filter and drain.

5.8.6.1.3 Embankment Surface During Winter Shutdown

In areas where frost penetration is expected, a loose protective cover several feet thick should be placed. When construction resumes, this protective layer is removed [63]. The worst damage that occurs in frozen material is a moderate loosening of the upper foot of the completed embankment due to frost action. If this loose surface layer is found, it should be excavated in the spring before the next lift is placed. The depth of stripping required can best be determined by visual evaluation of the upper portion of the embankment using shallow test pits. The key to any embankment protection scheme for winter shutdowns is to ensure that the material on which the first lift is placed in the spring is in full accordance with the specifications of all required properties.

5.8.7 Inspection and Field Tests

As described in the following sections, the quality of filter and drain construction in an embankment dam is accomplished both visually and by in-place testing. As described later, visual inspection is mandatory to get the most representative test results and highest construction quality.

5.8.7.1 Inspection

According to Dr. Ralph Peck, "There are few things of more importance in ensuring quality on a construction job than to have a set of eyes attached to a calibrated brain observing the construction operations" [64]. Regardless of the number of tests performed, they represent only a minute fraction of material that has been placed. Therefore, continuous visual inspection of field operations and conditions is the backbone of the quality control (QC) program and is vitally important to ensuring quality. Typical items an inspector should observe with respect to filter/drain/transition zone construction include the hauling, dumping, spreading, and compaction operations; condition of the in-place material; and protection of the completed work. In addition to observation, the inspector must call for testing to be performed at the locations the inspector determines to be questionable. All of these operations should be observed and monitored in compliance with the specification and proper construction practice.

To be most effective, inspectors must establish a reputation for being strict but fair. Inspection personnel must be experienced, knowledgeable of the plans and specifications, and good communicators. Early in the job, inspectors must make every effort to become "calibrated" to material characteristics and behavior in the construction process. This is necessary to lend credibility to the observations and to operate efficiently. By observing construction processes and material conditions, a properly calibrated inspector should have a very good idea whether placed material meets the specifications, even before testing is performed. Inspectors must communicate well, especially with contractor personnel. Experience has repeatedly shown that inspectors should establish good relations with contract personnel and explain to them the importance of removing contaminated material, maintaining specified minimum drain width, minimizing contamination, etc. When properly motivated by knowing the reasons for and importance of the work they are performing, laborers and equipment operators usually will take more pride in their work, resulting in more desire to do quality work. Documentation of inspection operations is very important and is in the form of inspection reports, which are prepared daily by the inspector. Supervisory personnel should review these reports daily to ensure adequacy of work performed.

5.8.7.2 Testing

Field and laboratory testing, together, provide verification of specification compliance for filter/drain and transition zone materials placed in an embankment. In addition, test results provide as-built documentation for the completed structure. Test results aid in the calibration process for QC personnel and help inform the contractor about what is expected to be achieved in the field. Like inspection, field and laboratory testing form an integral part of the QC program and are essential to obtaining product quality. Because of time constraints, most projects will require an onsite testing laboratory staffed with trained and experienced technicians. All inspection and laboratory technicians should also be experienced with the latest testing procedures and requirements.

5.8.7.2.1 Field Testing

One aspect of field testing for construction of filter/drain and transition zones consists of in-situ tests to determine dry density. End-result specifications require measurements to be made of the compacted filter/drain zone to determine specification compliance and for documentation. Construction testing for specification compliance is not required under a method-type specification. However, even when using method specifications, field measurements of the compacted density of the zones should periodically be made to ensure that the method specified is achieving the desired results and to provide as-built documentation. Field density tests should be performed using the sand cone method (ASTM D1556) as shown in figure 5.8.7.2.1-1. Reclamation testing data indicate that the nuclear meter frequently underestimates dry density [65], and it is not allowed for testing of granular materials in embankment dams without frequent calibration to the sand cone test. The test should be performed on the top surface of the underlying lift. It is very important to take care in preparing a proper surface and ensuring that the intended location and layer of material are being tested.

Figure 5.8.7.2.1-1. 'Sand Cone Test' being performed in a sand blanket filter.

5.8.7.2.2 Selection of Test Locations

The selection of field density test locations should be made by the inspector who has been observing construction operations. Factors that affect selection of test locations should be discussed with the technician performing the test. Improper selection often may cause more difficulty in practice than many of the errors in the test procedure itself. The test location should be selected with a view toward obtaining both the average percent compaction and the percent compaction in any area where the inspector suspects improper compaction has occurred. Overcompaction of sands could result in the development of fines at or near the lift surface, which could adversely affect the maximum percent fines requirement. Undercompaction may result in low density of in-place fill. Similarly, locations where samples for gradation verification testing are taken should also be selected by personnel who have observed placement and compaction operations. Gradation tests for specification compliance are performed on sand samples after compaction. As is the case with density tests, locations for gradation tests should be selected based on visually determining that the location selected is representative of the overall construction process. Selected locations may also be based on observations where the inspector suspects that the specified gradation has not been met.

5.8.7.2.3 Frequency of Testing

The frequency at which testing for density and gradation is performed should be established by the designer and specified. Test frequencies are normally based on a volume-placed basis, although increased testing may be required when the placement is in critical zones such as near outlet conduits or spillway walls where compaction may be difficult. Table 5.8.7.2.3-1 shows an example of frequency requirements specified by the designer for construction of an embankment dam. It is noted that the values shown represent minimum test frequencies. These frequencies should be increased during initial construction and when there are problems or other extenuating circumstances.

Table 5.8.7.2.3-1. Example of minimum testing frequency for QC and quality assurance (QA) for filter and transition materials on a project using a method specification for compaction

	Type of test	Number of tests filter (sand)	Number of tests transition (sand and gravel)
QC	Gradation	1 per 2,000 cubic yards	1 per 5,000 cubic yards
QC	Density	None required	None required
QA	Gradation	1 per 5,000 cubic yards	1 per 10,000 cubic yards
QA	Density	1 per 5,000 cubic yards	1 per 7,500 cubic yards

Note: The testing frequency shown is the minimum acceptable rate. More frequent testing may be required, at least one test per shift.

5.8.7.2.4 Reference Density

Several types of control tests have been[25] and are currently used to obtain reference density values for design and construction of granular filter zones. The primary types of tests used are:

- **Relative Density Test** – Minimum Index Density ASTM D4254, Maximum Index Density, ASTM D4253
- **Compaction (Proctor) Test**[25] – ASTM D698 and ASTM D1557
- **Vibratory Hammer Test** – ASTM D7382

The following sections discuss these tests for use in construction control in more detail.

5.8.7.2.5 Relative Density

Minimum and maximum index density tests can be performed on a wide range of filter materials ranging from fine concrete sand to gravels as described in ASTM D4253 and D4254. After establishing the minimum index density and the maximum index density for the material, the in-place value is established that provides the basis for permeability and shear strength values. This in-place (intermediate) value is known as the relative density. Using this procedure, typically a minimum relative density of 70 percent has been typically specified as the required density for granular materials. Using relative density to control the placement of granular filters has a long tradition, but problems with the test have caused designers to explore other methods for establishing design densities and writing specifications for placement. Problems with the relative density test include:

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[25] Some tests are no longer used due to their incorrect application in granular soils.

- Difficulty in calibrating the vibrating table used for the maximum index density test
- Poor repeatability of test – lack of precision
- Lack of equipment near construction site and cost of tests

Tavenas et al. [66] and Holtz [67] describe problems with the use of relative density in construction control. They report unacceptably large deviations in test results on a standard sample between laboratories. Their studies show that results from the minimum and maximum index density tests are subject to large variations, even though standardized procedures were prescribed for the testing. Tests showed a wide confidence interval, for example the 95-percent confidence interval for clean sand covered a range of 6.8 lb/ft^3. In addition to the above problems with the test itself, performance of the test is time consuming and is therefore not conducive for compliance testing during construction.

5.8.7.2.6 Proctor Maximum Density

Determination of maximum density by what is commonly known as the "Proctor" or impact compaction test has been utilized for many decades. There are two basic types of this test, the difference being the amount of energy used to compact the soil. Since the Proctor test is used primarily for impervious soils where maximum density and optimum water content values are needed, it is rarely used for pervious soils and should **not be used**. Typical moisture-density curves for a clean sand are shown in figure 5.8.5.3-1, which indicate that the maximum density for these types of materials occurs when the material is nearly dry or completely saturated

5.8.7.2.7 Vibratory Hammer Compaction Test

Another development in obtaining index density values for clean sands is a test using a vibratory hammer (figure 5.8.7.2.7-1 shows the equipment). Prochaska [70] and Drnevich et al. [71] discuss the test in detail. The test is ASTM Test Standard, ASTM D7382. A reference density is obtained in the test by compacting a sample of filter into a steel mold with a hammer using three lifts to fill the mold. Either the filter is oven dry or saturated during the test. Two sizes of mold are used. A 6-inch-diameter mold is used for filters with a maximum particle size of 3/4 inch, and an 11-inch-diameter mold is used for filters with particles with a maximum size up to 2 inches in diameter. The value obtained for the vibrated dry density is used as a reference density for laboratory tests and can be used in contract language to specify a minimum acceptable density for the material tested.

Figure 5.8.7.2.7-1. Vibratory hammer used to obtain a reference density value for filter materials. (Photo courtesy of Dr. Vincent Drnevich.)

5.8.7.2.8   Gradation

Laboratory testing of sand samples for gradation compliance is accomplished by using the test method presented in ASTM D422, “Standard Method for Particle Size Analysis of Soils.” In cases where a quick check is useful (as perhaps percent passing the No. 200 sieve size), a partial gradation may be performed. Otherwise, the sieves used in the test should be the same size and number as presented in the specification.

5.8.8 Protection of Pipes

Proper methods for installing plastic pipe are described in FEMA P-676. Horizontal drains are often used to collect seepage, typically in toe drains. A number of poor practices are commonly encountered in pipe installation and should be avoided. They include, but are not limited to:

- Compaction of backfill using the backhoe bucket by “thumping” or setting the bucket on the backfill and lifting the back of the backhoe by applying pressure to the bucket

- Wheel rolling, either parallel or transverse, to the pipe by any type of construction equipment or vehicle

- Not placing or fully compacting backfill under haunches of the pipe

- Haul roads or equipment crossing the pipe without sufficient cover

A minimum depth of 4 feet should be provided over the top of the pipe for H-20 highway truck loading (front axle load of 8,000 pounds and rear axle load of 52,000 pounds) in accordance with AASHTO (more depth may be required if recommended by the manufacturer). Note that crossing over a pipe at a low point in the haul road will lead to higher-than-normal loads due to braking. In a similar fashion, a poorly maintained and uneven haul road will lead to bouncing, which also results in higher loads. If the haul road is poorly maintained or does not have a uniform grade, traffic speed should be restricted to no more than 5 miles per hour at the crossing. Recommendations for the type of pipe to use for these loading conditions are presented in section 5.2.3.2. To confirm that installed pipes have not been damaged, it is recommended that a video inspection be made soon after 4 feet of permanent fill has been placed over the pipe.

5.9 Glossary

Absorption – The increase in the weight of aggregate due to water in the pores of the material, but not including water adhering to the outside surface of the particles, expressed as a percentage of the dry weight. The aggregate is considered "dry" when it has been maintained at a temperature of 110 plus or minus 5 degrees Celsius for sufficient time to remove all uncombined water.

Abutment – That part of the valley wall against which the dam is constructed. Left and right abutments are defined on the basis of looking in the downstream direction.

Anisotropy – Variability of a soil causing the horizontal permeability to be different than the vertical permeability. Typically, natural deposits and manmade fill will have greater horizontal than vertical permeability because they are placed in a horizontal fashion, causing them to be stratified.

Apparent specific gravity – The ratio of the weight in air of a unit volume of the impermeable portion of aggregate at a stated temperature to the weight in air of an equal volume of gas-free distilled water at a stated temperature.

Arching – The soil property in which stresses distribute onto stiffer elements, such as rock formation or a concrete structure, in such a way that the vertical stresses over softer areas are less than the overburden pressure.

Backward erosion piping – Erosion of soil that begins from a concentrated seepage location, usually in the downstream area of a dam. As the erosion continues, more and more material is removed, resulting in a pipe-shaped void. This erosion continues upstream towards the highest gradient or backward from the initiation point.

Base soil – The soil material that is being protected by a filter. Base soils are upgradient of the filter.

Bedrock – A general term that includes any of the generally indurated or crystalline materials that make up part of the Earth's crust. Individual stratigraphic units or units significant to engineering geology within bedrock may include poorly or nonindurated materials such as beds, lenses, or intercalations.

Binding agents – Material, either mineral or chemical, that coats filter material, resulting in the filter particles being cemented or bound together.

Blanket – A layer or zone parallel to the foundation in an embankment dam between the downstream shell and foundation. It typically provides drainage from the chimney filter to the toe drain. Also see "Drainage blanket."

Blanket drain – The second stage of a filter/drain blanket system consisting of primarily gravel-size material.

Blanket filter – The first stage of a filter/drain blanket system consisting of primarily sand-size material.

Broadly graded – A characteristic of a soil gradation where a variety of soil grain sizes are present.

Category 1 soil – Base soil that has more than 85 percent fines after regrading.

Category 2 soil – Base soil that has between 40 and 85 percent fines after regrading.

Category 3 soil – Base soil that has between 15 and 40 percent fines after regrading.

Category 4 soil – Base soil that has less than 15 percent fines after regrading.

Cementing agents – Chemicals, usually in solution form, that coat filter aggregate. These agents are not detected using grain size analysis and will not classify as fines using the USCS.

Chimney – A zone in an embankment dam that extends from the foundation to near the top of the dam. Chimneys can be vertical or inclined.

Chimney drain – The second stage of a filter/drain chimney system consisting of primarily gravel-size material.

Chimney filter – The first stage of a filter/drain chimney system consisting primarily of sand-size material.

Clean – A soil gradation that contains less than 5 percent fines by weight.

Coefficient of curvature (also coefficient of gradation) – Determined from a grain-size analysis, calculated from the relationship: $C_z = D_{30}^2/(D_{60} * D_{10})$ where D_{60}, D_{30}, and D_{10} are the particle diameters corresponding to 60, 30, and 10 percent finer on the cumulative gradation curve, respectively.

Coefficient of gradation – See "Coefficient of curvature."

Coefficient of internal friction – The tangent of the angle of internal friction.

Coefficient of uniformity – Determined from a grain-size analysis, equal to the ratios D_{60} / D_{10}, where D_{60}, and D_{10} are the particle diameters corresponding to 60 and 10 percent finer on the cumulative gradation curve, respectively.

Compaction – Mechanical action that increases density by reducing the voids in a material.

- *End Result* – A compaction process that includes requirements for density, moisture content, and other criteria to ensure that the compacted soil has the intended properties.
- *Method* – A compaction process that only specifies the initial lift thickness, equipment, and its operation in compacting the soil.

Compactor – Machinery or device used to increase the density of soil. Also see "Roller."

Conduit – Typically a pipe, box, or horseshoe structure that is constructed by means of "cut and cover." A conduit can convey water or house other conduits, pipes, cables, wires, etc.

Core – In a zoned embankment, the core usually is the portion of the embankment having the lowest permeability and is intended to limit the quantity of seepage through the embankment to an acceptable amount.

Coverage – The amount of surface area that is compacted in one trip. For steel drum rollers, the coverage is 100 percent. For rubber-tire rollers, the coverage is 50 percent due to the space between the tires. Therefore, two passes/trips are required to obtain 100-percent coverage.

Crack – A long, narrow opening or a separation in previously intact material. Also see "Longitudinal crack" and "Transverse crack."

Critical gradient – The gradient at which seepage will cause soil particles to begin to move. In cases where seepage exits the ground surface vertically, the critical gradient is calculated as unity when the specific gravity is 2.74. Soils that have a different specific gravity will have a different critical gradient.

Cutoff trench – An excavation in the foundation of an embankment dam below the original streambed elevation that is intended to reduce underseepage.

Cutoff wall – A vertical barrier under a dam, usually constructed in a deep vertically sided trench. The backfill in the trench can be a variety of materials including concrete, soil-bentonite, and soil-cement-bentonite. A wall of impervious material (e.g., concrete, timber, steel sheet piling) located in the foundation beneath the dam, which forms a water barrier to reduce underseepage.

Dam – An artificial barrier that has the ability to impound water, wastewater, or any liquid-borne material for the purpose of storage or control of water.

- *Earthfill* – An embankment dam in which more than 50 percent of the total volume is formed of compacted earth layers comprised of material generally smaller than 3 inches.

- *Embankment* – Any dam constructed of excavated natural materials, such as both earthfill and rockfill dams, or of industrial waste materials, such as a tailings dams.

- *Rockfill* – An embankment dam in which more than 50 percent of the total volume is comprised of compacted or dumped cobbles, boulders, rock fragments, or quarried rock generally larger than 3 inches.

- *Tailings* – An industrial waste dam in which the waste materials come from mining operations or mineral processing.

Dam height – The vertical difference between the lowest point in the original streambed at the dam axis (or the crest centerline) and the crest of the dam.

Defect – An anomaly in an earthfill dam such as a crack, poorly placed lift, or separation between the fill and concrete structure.

Deformation – A change in dimension or shape due to stress.

Diaphragm – A filter zone used to protect a conduit against internal erosion along the outside of the conduit. The filter thickness is 'thin' (about 8-feet) relative to the entire dam cross section. When used to protect an existing conduit alone it has limited extent vertically and horizontally. When used to protect existing conduits in addition to adding a chimney filter to an existing dam, it is part of that chimney filter. Also see envelope.

Discharge face – The downstream face of the base soil through which seepage flow passes.

Discharge point – The end of a drain system where flow is discharged into some other watercourse or drainageway.

Dispersive soil – Clay soil that has higher than typical erosion potential due to its uncommon characteristic of dispersing into seepage flow similar to going into solution.

Drain – Typically, a second stage of a filter/drain system consisting of gravel. A feature designed to collect water and convey it to a discharge location. Typically, a drain is intended to relieve excess water pressures.

Drainage blanket – An embankment zone that provides drainage from the base of the chimney to the downstream toe area of a dam.

Drainpipe – A system of pipe within an embankment dam used to collect seepage from the foundation and embankment and convey it to a free outlet.

Envelope – A protective filter that is used to envelope a conduit or other penetration through an embankment dam. Also see diaphragm.

Erosion – Removal of soil grains by either surface water flow or seepage through the ground.

Failure – A circumstance in which uncontrolled releases of reservoir water from a dam occur that have an adverse impact on downstream persons or property.

Failure mode – A physically plausible process for an embankment dam failure, resulting from an existing inadequacy or defect related to a natural foundation condition, the dam or appurtenant structure's design, the construction, the materials incorporated, the operation and maintenance, or aging process, which can lead to an uncontrolled release of the reservoir.

Filter – A zone of material designed and installed to provide drainage, yet prevent the movement of soil particles due to flowing water. A material or constructed zone of earthfill that is designed to permit the passage of flowing water through it but prevents the passage of significant amounts of suspended solids through it by the flowing water.

- *Chimney* – A chimney filter is a vertical or sloping element in an embankment dam that is placed immediately downstream of the dam's core. The chimney filter is typically placed in the central portion of the dam.

- *Collar* – A limited placement of filter material that completely surrounds a conduit for a specified length within the embankment dam. The filter collar is usually included in embankment dam rehabilitation only when a filter diaphragm cannot be constructed. The filter collar is usually located near the conduit's downstream end. A filter collar is different from a filter diaphragm in that a filter diaphragm is usually located within the interior of the embankment dam.

- *Diaphragm* – A filter diaphragm is a zone of filter material constructed as a diaphragm surrounding a conduit through an embankment. The filter diaphragm protects the embankment near the conduit from internal erosion by intercepting potential cracks in the earthfill near and surrounding the conduit. A filter diaphragm is intermediate in size between a chimney filter and a filter collar. The filter diaphragm is placed on all sides of the conduit when the conduit is founded on soil and extends a specified distance into the embankment.

Filter cake – A thin layer of soil particles that accumulate at the face of a filter when water flowing through a crack in the upstream zone carries eroding particles to the filter face. The filter cake forms when eroded particles embed themselves into the surface near voids of the filter. The filter cake is effective in reducing further waterflow and erosion through the crack.

Filter collar – See "Filter, collar."

Filter diaphragm – See "Filter, diaphragm."

Fines – The soil grain sizes that are smaller than the No. 200 sieve (0.075 mm) as used in the USCS.

First filling – Usually refers to the initial filling of a reservoir or conduit. After major repairs, the refilling of the reservoir may also be referred to a first filling.

First stage – The initial stage of a filter/drain system usually consisting of filter sand. The first stage protects foundation soils or impervious core.

Flexible pipe – A pipe that derives its load carrying capacity by deflecting at least 2 percent into the surrounding medium upon application of load.

Flood – A temporary rise in water surface elevation resulting in inundation of areas not normally covered by water.

Forensics – The branch of science that employs scientific technology to assist in the determination of facts. Specifically for earthfill structures, the examination of the failure area in order to determine the cause of failure.

Foundation – The portion of a valley floor that underlies and supports an embankment dam. Soil or rock materials present at the damsite upon which a dam is built. Foundation materials that are consolidated into rock or rock-like material may be referred to as bedrock, while unconsolidated materials such as clay, sand, or gravel may be referred to as surficial materials.

Gap-graded – A soil property in which a particular soil grain size is missing from the central portion of the gradation curve, such as when no fine sand grain sizes are present in a sand and gravel soil, there is a "gap" in the fine sand size. Also known as skip-graded.

Geotextiles – Any fabric or textile (natural or synthetic) when used as an engineering material in conjunction with soil, foundations, or rock. Geotextiles have the following uses: drainage, filtration, separation of materials, reinforcement, moisture barriers, and erosion protection.

Gradation – The distribution of particles of granular material among standard sizes usually expressed in terms of cumulative percentages larger or smaller than each of a series of sieve openings.

Gradation band – The range of particle sizes for which a filter gradation is specified. The gradation band must fit within the limits determined by the filter design procedure. Also see "Limits."

Gradient – The change in head loss of a given distance. Also the property used to evaluate the potential for seepage water to move (erode) a soil particle.

Grain size distribution – A visual representation of the percentage of specified soil particle sizes relative to one another.

Gravel – Materials that will pass a 3-inch (76.2-millimeter [mm]) and be retained on a No. 4 (4.75-micrometer [µm]) U.S. standard sieve.

Groin – The line of contact between the face of the dam (upstream or downstream) and the abutment.

Grout – A fluidized material that is injected into soil, rock, concrete, or other construction material to seal openings and to lower the permeability and/or provide additional structural strength. There are four major types of grouting materials: chemical, cement, clay, and bitumen.

Grout mix – The proportions or amounts of the various materials used in the grout, expressed by weight or volume (the words "by volume" or "by weight" should be used to specify the mix).

Grout pipe – The pipe used to transport grout to a certain location. The grout may be transported through this pipe by either gravity flow or pressure injection.

Hazard – A situation that creates the potential for adverse consequences such as loss of life or property damage.

Hazard potential classification – A system that categorizes embankment dams according to the degree of adverse incremental consequences of a failure or misoperation of a dam. The hazard potential classification does not reflect in any way on the current condition of the embankment dam (i.e., safety, structural integrity, flood routing capacity).

Head – The vertical difference, typically expressed in feet, between two water surface elevations.

Height (above ground) – The maximum height from natural ground surface to the top of an embankment dam.

Heterogeneous – Consisting of dissimilar constituents. For soils, consisting of several soil types.

High density polyethylene (HDPE) – A polymer prepared by the polymerization of ethylene as the sole monomer.

Homogeneous – Consisting of similar constituents. For soil, consisting of a single soil type.

Hydraulic conductivity – The ease at which water can flow though a soil. The *coefficient* of hydraulic conductivity is a property of a soil in which the waterflow through the soil is a function of the gradient and cross sectional area of the flow path.

Hydraulic fracture – A separation in a soil or rock mass that occurs if the applied water pressure exceeds the lateral effective stress in the mass. Hydraulic fracture may occur in vertical cracks transverse to the dam axis or other defects. Soils compacted dry of optimum water content are more susceptible to hydraulic fracture.

Hydraulic gradient – The slope of the hydraulic grade line. The hydraulic gradient is the slope of the water surface in an open channel.

Hydraulic height – The vertical difference between the lowest point in the original streambed at the dam axis (or the centerline crest of the dam) and the maximum controllable water surface (which often is the crest of an uncontrolled overflow spillway).

Hydraulic structure – Any structure that retains or carries water (dams, levees, canals, spillways, retaining walls, etc.).

Hydrophilic – Having a strong affinity for water.

Hydrophobic – Having a strong aversion to water.

Hydrostatic head – The fluid pressure of water produced by the height of the water above a given point.

Hydrostatic pressure – The pressure exerted by water at rest.

Ice lens – A mass of ice and soil formed during the construction of an embankment dam when a moist soil is exposed to freezing temperatures. In certain types of soils (silts and silty clay soils), the size of the ice mass will increase as it draws unfrozen capillary water from the adjacent soil. A loose soil lense containing voids may remain after the ice lens melts.

Impervious – Not permeable; not allowing liquid to pass through easily. In relation to embankment dams, the material intended to act as the water barrier.

Incident – Either a failure or accident that requires a major repair.

Inclined filter – A sloping embankment filter zone located near the control portion of the cross section. Also see “Chimney.”

Infiltration – The flow of water through a soil surface or the flow of water into a conduit through a perforation, joint, or defect.

Inspection – The review and assessment of the operation, maintenance, and condition of a structure.

Inspector – The designated onsite representative responsible for inspection and acceptance, approval, or rejection of work performed as set forth in the contract specifications. The authorized person charged with the task of performing a physical examination and preparing documentation for inspection of the embankment dam and appurtenant structures.

Instrumentation – An arrangement of devices installed into or near embankment dams that provide for measurements that can be used to evaluate the structural behavior and performance parameters of the structure.

Intergranular flow path – Flow of water through the voids or pore spaces of a soil.

Internal erosion – A general term used to describe all of the various erosional processes in which water moves internally through or adjacent to the soil zones of embankment dams and foundation. The term “internal erosion” is used in this document in place of a variety of terms that have been used to describe various erosional processes such as scour, suffosion, concentrated leak piping, and others. A term used to describe the process of erosion of dam or foundation soils by flowing water, which includes erosion by such mechanisms as scour, internal instability of soils, heave, or “piping.”

Internal instability – A property of soil in which particles can move within the mass itself.

Inundation map – A map showing areas that would be affected by flooding from releases from a dam’s reservoir. The flooding may be from either controlled or uncontrolled releases or as a result of a dam failure. A series of maps for a dam could show the incremental areas flooded by larger flood releases.

Inverted filter – A filter placed in reverse order in an effort to stop material erosion from a concentrated seepage area. The second stage (gravel) is placed first to attenuate the flow of water. Next, the first stage (sand) is placed to stop the material erosion.

Isotropy – Uniformity of a soil in that the horizontal permeability is the same as the vertical permeability.

Leakage – Uncontrolled loss of water by flow through a hole or crack.

Lift – A soil layer of a given thickness placed during embankment construction.

Limits – The control points, as determined by the design procedures, in which a filter gradation must fit so filter criteria are met.

Liquefaction – A sudden loss of strength in saturated soils caused by an increase in pore pressure, which results from low density soils being subjected to earthquake shaking. This loss of strength in embankment or foundation soils could result in a slope failure of the dam.

Loess – Silt which is transported by the wind over many miles, sometimes hundreds of miles, and deposited in deposits in thickness of several inches to several hundred feet. Many loess deposits are nonplastic and have little erosion resistance.

Longitudinal crack – A crack in an embankment dam somewhat parallel to the axis (centerline) of the dam.

Maintenance – All routine and extraordinary work necessary to keep a facility in good repair and reliable working order to fulfill the intended designed project purposes. This includes maintaining structures and equipment in the intended operating condition and performing necessary equipment and minor structure repairs.

Maximum water surface – The reservoir water surface that results from the inflow design flood.

Moisture content – See "Water content."

Monitoring – The process of measuring, observing, or keeping track of something for a specific period of time or at specified intervals.

Multilayer filter – A filter/drain system consisting of more than one stage (i.e., a two-stage filter).

Normal water surface – For a reservoir with a fixed overflow sill, this is the lowest crest level of that sill. For a reservoir with an outflow controlled wholly or partly by moveable gates, siphons, or other means, it is the maximum level to which water may rise under normal operating conditions, exclusive of any provision for flood surcharge.

Nuclear gauge – An instrument used to measure the density and water content of both natural and compacted soil, rock, and concrete masses. The gauge obtains density and water contents from measurements of gamma rays and neutrons that are emitted from the meter. Gamma rays are emitted from a probe inserted into the mass being measured. Measurement of the gamma rays transmitted through the mass, when calibrated properly, reflects the density of the mass. Neutrons are emitted from the base of the gauge. Measuring the return of reflected neutrons when the gauge is calibrated properly can be related to the water content of the mass.

Open cut – An excavation through rock or soil made through topographic features.

Optimum moisture content (optimum water content) – The water content at which a soil can be compacted to a maximum dry unit weight by a given compactive effort.

Outlet works – An embankment dam appurtenance that provides release of water (generally controlled) from a reservoir. A tunnel, conduit, or pipe provided at a dam through which normal releases from the reservoir can be made.

Overburden – The soil that overlies bedrock.

Passes – One trip for a single-drum roller. When a roller has two drums, one trip is equal to two passes.

Perforated pipe – A pipe intended to collect seepage through holes or slots on its exterior.

Permeability – The ease at which water or other fluid, including gasses, can flow through a material.

Pervious – Permeable, having openings that allow water to pass through.

Pervious zone – A part of the cross section of an embankment dam comprising material of high permeability.

Phreatic line – Water surface boundary. Below this line, soils are assumed to be saturated. Above this line, soils contain both gas and water within the pore spaces.

Phreatic surface – The planar surface between the zone of saturation and the zone of aeration. Also known as free-water surface, free-water elevation, ground water surface, and ground water table. The top of the zone of saturation in an embankment. Seepage through the embankment causes the saturation, and the location of the phreatic surface typically varies in response to changing reservoir and tailwater conditions.

Piezometer – An instrument for measuring fluid pressure (air or water) within soil, rock, or concrete. A device for measuring the pore water pressure at a specific location in earthfill or foundation materials.

Pipe – A hollow cylinder of concrete, plastic, or metal used for the conveyance of water.

- *Cast iron* – A type of iron-based metallic alloy pipe made by casting in a mold.
- *Corrugated metal* – A galvanized light gauge metal pipe that is ribbed to improve its strength.
- *Ductile iron* – A type of iron-based metallic alloy pipe that is wrought into shape.
- *Plastic* – A hollow cylinder of plastic material in which the wall thicknesses are usually small when compared to the diameter and in which the inside and outside walls are essentially concentric.
- *Precast concrete* – Concrete pipe that is manufactured at a plant.
- *Steel* – A type of iron-based metallic alloy pipe having less carbon content than cast iron but more than ductile iron.

Piping – The removal of embankment or foundation material by flowing water through a cross section of limited size (initially) because of the ability of the embankment or foundation to provide a “roof” that does not significantly collapse into the developing “pipe.” Progresses upstream from a downstream exit location and can lead to dam failure if the developing “pipe” reaches the reservoir or if the enlarging pipe collapses and results in crest loss that leads to overtopping. Similar to subsurface erosion or internal erosion by seepage flow, except only true piping involves the capability to provide a “roof” that reduces the amount of embankment or foundation material that needs to be transported by the seepage flow to extend the flow path from the downstream exit to the reservoir. Also see “Backward erosion piping.”

Plasticity – A soil property indicating moldability or ability to remold.

Pore pressure – The interstitial pressure of a fluid (air or water) within a mass of soil, rock, or concrete.

Preferential flow path – A crack in a soil mass or a separation between soil and a structure or rock contact.

Pull-a-part – A geologic condition of foundation rock where geologic processes have resulted in tensile zones at the rock surface. These tensile zones result in large joint and fracture separations. Processes that can lead to these tensile zones are concentrated uplift resulting in a convex surface or dipping beds as seen in hogbacks that can slip down dip.

Quality assurance – A planned system of activities that provides the owner and permitting agency assurance that the facility was constructed as specified in the design. Construction quality assurance includes inspections, verifications, audits, and evaluations of materials and workmanship necessary to determine and document the quality of the constructed facility. Quality assurance refers to measures taken by the construction quality assurance organization to assess if the installer or contractor is in compliance with the plans and specifications for a project. An example of a quality assurance activity is verifications of quality control tests performed by the contractor using independent equipment and methods.

Quality control – A planned system of inspections that is used to directly monitor and control the quality of a construction project. Construction quality control is normally performed by the contractor and is necessary to achieve quality in the constructed system. Construction quality control refers to measures taken by the contractor to determine compliance with the requirements for materials and workmanship as stated in the plans and specifications for the project. An example of a quality control activity is the testing performed on compacted earthfill to measure the dry density and water content. By comparing measured values to the specifications for these values based on the design, the quality of the earthfill is controlled.

Refilling – The procedure of filling a reservoir after it has previously held water, typically after a modification to an existing dam.

Regrading – The mathematical procedure of removing a certain fraction of an original gradation, such as removing all gravel sizes (regrading on the No. 4 sieve size).

Relative density – A numerical expression that defines the relative denseness of a cohesionless soil. The expression is based on comparing the density of a soil mass at a given condition to extreme values of density determined by standard tests that describe the minimum and maximum index densities of the soil. Relative density is the ratio, expressed as a percentage, of the difference between the maximum index void ratio and any given void ratio of a cohesionless, free-draining soil to the difference between its maximum and minimum index void ratios.

Relief well – A vertical well near the downstream toe of the dam used to relieve pressure in a deeper foundation layer that is under high pressure.

Repair – The reconstruction or restoration of any part of an existing structure for the purpose of its maintenance.

Replacement – The removal of existing materials that can no longer perform their intended function and installation of a suitable substitute.

Reservoir – A body of water impounded by an embankment dam and in which water can be stored.

Reservoir evacuation – The release or draining of a reservoir through an outlet works, spillway, or other feature at an embankment dam.

Riprap – A layer of large, uncoursed stone; precast blocks; bags of cement; or other suitable material generally placed on the slope of an embankment or along a watercourse as protection against wave action, erosion, or scour. Riprap is usually placed by dumping or other mechanical methods and, in some cases, is hand placed. It consists of pieces of relatively large size as distinguished from a gravel blanket. Rock fragments, rock, or boulders placed on the upstream or downstream faces of embankment dams to provide protection from erosion caused by wind or wave action.

Riprap bedding – The bedding layer under riprap usually consisting of gravel and cobble size material. The purpose of the bedding is to provide for riprap embedment and a transition between the riprap and upstream shell or core of the dam as the case may be.

Risk – A measure of the likelihood and severity of adverse consequences.

Rock – Lithified or indurated crystalline or noncrystalline materials. Rock is encountered in masses and as large fragments, which have consequences to design and construction differing from those of soil.

Rockfill dam – See "Dam, rockfill."

Roller – Machinery used to increase the density of soil that typically rolls across the fill on a drum. Also see "Compactor."

Rutting – The tire or equipment impressions in the surface of a compacted fill that result from repeated passes of the equipment over the compacted fill when the soil is at a moisture and density condition that allows the rutting to occur. Rutting usually occurs when soils are not well compacted and/or are at a water content too high for effective compaction.

Sand – Particles of rock that will pass the No. 4 (4.75-µm) sieve and be retained on the No. 200 (0.075-mm) U.S. standard sieve.

Sand boil – Sand or silt grains deposited by seepage discharging at the ground surface without a filter to block the soil movement. The sand boil may have the shape of a volcano cone with flat to steeper slopes, depending on the size and gradation of particles being piped. Sand boils are evidence of piping occurring in the foundation of embankments or levees from excessive hydraulic gradient at the point of discharge. Seepage emerging downstream of a dam, characterized by a boiling action at the surface and typically surrounded by a ring of material (caused by deposition of foundation and/or embankment material carried by the seepage flow).

Scour – The loss of material occurring at an erosional surface where a concentrated flow is located, such as a crack through a dam or the dam/foundation contact. Continued flow causes the erosion to progress, creating a larger and larger eroded area.

Second stage – The second stage of a filter/drain system usually consisting of gravel. The second stage protects the first stage and surrounds the drainpipe in toe drain systems.

Secondary defensive elements – Embankment zones that have a purpose to protect the core and foundation if an unexpected defect or condition presents itself. Also see “Filter.”

Sediment trap – A containment area in which flow velocity is reduced so soil particles can settle out.

Seepage – The infiltration or percolation of water through rock or soil or from the surface.

Segregation – The tendency of particles of the same size in a given mass of aggregate to gather together whenever the material is being loaded, transported, or otherwise disturbed. Segregation of filters can cause pockets of coarse and fine zones that may not be filter compatible with the material being protected.

Seismic activity – The result of the earth’s tectonic movement.

Self-healing – The property of a soil in which soil particles rearrange themselves until they are stable. Also rearrangement of base soil particles against the face of a filter.

Settlement – The vertical downward movement of a structure or its foundation.

Shear strength – The ability of a material to resist forces tending to cause movement along an interior planer surface.

Shear stress – Stress acting parallel to the surface of the plane being considered.

Shell – In a zoned embankment, a shell zone typically is provided downstream of the core of the embankment and may be provided upstream of the core as well, to provide stability to the dam embankment. Shell zones typically have significantly higher permeability and shear strength than the core.

Silt – Material passing the No. 200 (75-µm) U.S. standard sieve that is nonplastic or very slightly plastic and that exhibits little or no strength when air dried.

Single-stage filter – A filter consisting of a single material.

Sinkhole – A depression, indicating subsurface settlement or particle movement, typically having clearly defined boundaries with a sharp offset. A steep-sided depression formed when removal of subsurface embankment or foundation material causes overlying material to collapse into the resulting void.

Slaking – Degradation of excavated foundation caused by exposure to air and moisture.

Slope – Inclination from the horizontal. Sometimes referred to as batter when measured from vertical.

Slotted pipe – See "Perforated pipe."

Slough – See "Slump."

Slump – Movement of a soil mass downward along a slope.

Slurry – A mixture of solids and liquids.

Soil – An earth material consisting of three components: solids (mineral particles), liquids (usually water), and gasses (air).

Soluble salt – A salt that can be dissolved in water.

Specifications – The written requirements for materials, equipment, construction systems, and standards.

Spillway – A structure that passes floodflows in a manner that protects the structural integrity of the darn. Where more than one spillway is present at a dam, the service spillway begins flowing first, followed by the auxiliary spillway (if three spillways are present), and, finally, the emergency spillway.

Stability – The resistance to sliding, overturning, or collapsing.

Standard Proctor compaction test – A standard laboratory or field test procedure performed on soil to measure the maximum dry density and optimum water content of the soil. The test uses standard energy and methods specified in ASTM Standard Test Method D 698.

Standards – Commonly used and accepted as an authority.

Static stability – The stability of a structure which is typically evaluated as a factor of safety against sliding, overturning, or slope failure.

Storage – The retention of water or delay of runoff either by planned operation, as in a reservoir, or by temporary filling of overflow areas, as in the progression of a flood wave through a natural stream channel.

Strip outlet drains – Drainage material placed in strips perpendicular to the dam axis under the downstream shell used to connect the base of the chimney with the downstream toe.

Structural height – The vertical distance from the lowest point of the excavated foundation (excluding narrow fault zones) to the top of the dam.

Subsidence – A depression, indicating subsurface settlement or particle movement, typically not having clearly defined boundaries.

Suffosion – Seepage flow through a material that causes part of the finer grained portions of the soil matrix to be carried through the coarser grained portion of the matrix. This type of internal erosion is specifically relegated only to gap-graded soils (internally unstable soils) or to soils with an overall smooth gradation curve, but with an overabundance of the finer portions of the curve represented by a "flat tail" to the gradation curve. While a crack is not needed to initiate this type of internal erosion, a concentration of flow in a portion of the soil is needed.

Surficial deposits – The relatively younger materials occurring at or near the Earth's surface overlying bedrock. They occur as two major classes: (1) deposits generally derived from bedrock materials that have been transported by water, wind, ice, gravity, and man's intervention; and (2) residual deposits formed in place as a result of weathering processes. Surficial deposits may be stratified or unstratified and may be partially indurated or cemented by silicates, oxides, carbonates, or other chemicals (caliche or hardpan).

Tailwater – The elevation of the free water surface (if any) on the downstream side of an embankment dam.

Toe drain – A drain typically located near the downstream toe of a dam, although drains under the downstream shell and downstream of the toe of the dam are also considered toe drains. The purpose of the drain is to gather flow from the chimney and blanket, if provided, and to collect seepage from the foundation. Toe drains can be either single-stage or two-stage filter/drain systems and may or may not include a collection pipe. The collection pipe can be open-jointed tile or perforated pipe located at or near the toe of the dam that functions to collect seepage and convey the seepage to a downstream outfall.

Toe of the embankment dam – The junction of the downstream slope or face of a dam with the ground surface; also referred to as the downstream toe. The junction of the upstream slope with ground surface is the upstream toe.

Transition zone – A zone in an embankment dam that provides a transition in grain size between two zones that are not filter compatible (i.e., one zone does not meet the particle retention criteria for the other). An example of a transition zone would be a zone required between a clayey gravel core and a downstream cobble shell.

Transverse crack – A crack that trends in an upstream and downstream direction within or through an embankment dam.

Trench – A narrow excavation (in relation to its length) made below the surface of the ground.

Trip – The single movement of a piece of compaction equipment from beginning to end of a section of material being compacted.

Two-stage filter – A filter consisting of two materials. The materials are typically a sand filter used to protect the foundation and a gravel drain used as the transition around a perforated collector pipe. In this example, the filter would also be known as stage 1 and the gravel as stage 2.

Tunnel – A long underground excavation with two or more openings to the surface, usually having a uniform cross section, used for access, conveying flows, etc.

Turbidity meter – A device that measures the loss of a light beam as it passes through a solution with particles large enough to scatter the light.

Uniform gradation or uniformly graded – A soil gradation consisting primarily of soils grains that are near the same size.

Unwater – Removal of surface water; removal of visible water; removal of water from within a conduit.

Uplift – The pressure in the upward direction against the bottom of a structure such as an embankment dam or conduit or a soil stratum.

Upstream blanket – An impervious soil layer placed upstream of the dam and connected to the core. The purpose of an upstream blanket is to increase the seepage path length under the dam on pervious foundations.

Vertical filter – A zone in an embankment dam near the embankment midsection which has vertical side slopes. Also known as a chimney or chimney filter.

Void – A hole or cavity within the foundation or within the embankment materials.

Water content – The ratio of the mass of water contained in the pore spaces of soil or rock material, to the solid mass of particles in that material, expressed as a percentage.

Weir – A barrier in a waterway over which water flows, serving to regulate the water level or measure flow. A device designed to allow the accurate measurement of the flow rate of drain flows, seepage flows, etc., by forcing the water to flow through a standardized opening, and measuring the elevation differential between the water surface in the stilling pool in front of the weir and the weir crest elevation, using a staff gauge set back an appropriate distance from the weir. When a weir is installed in a standard manner, charts are available for correlating staff gauge readings with flow rates. Types of weirs include Cipolletti, rectangular, and V-notch.

Well-graded – A soil gradation consisting of several soil sizes that form a smooth gradation curve when plotted on a logarithmic scale.

Zone – An area or portion of an embankment dam constructed using similar materials and similar construction and compaction methods throughout.

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Appendix A

Filtering and Transmissibility Needs of Drains in Dams and Other Water-Impounding Structures

by Harry R. Cedergren

Appendix A

Filtering and Transmissibility Needs of Drains in Dams and Other Water-Impounding Structures

Paragraph 5.1.11 emphasizes the idea that whenever the discharge capacity (transmissibility) needs of drains are important, a seepage analysis can be as important as an analysis of filtering requirements. This appendix illustrates typical situations where transmissibility is as vital as filter protection.

Figure A-1a shows a vertical "chimney" drain in a dam, and an outlet blanket drain. Each of these two parts of the system has a "filter" layer against the soil from which water is entering the drain (zone 1), an internal coarse gravel or crushed rock drain for discharge of the water (zone 2), and a transition zone to protect the coarse layer against contamination from adjacent embankment material (zone 3). The No. 1 zones are true "filters" and must be designed using the *Filter Criteria* given in this chapter. When the filters are of large expanse and provide large inflow areas for seepage, and there are no severe concentrations or converging flow, as in figure A-1a, the standard filter criteria generally will ensure that filters will be "somewhat" more permeable than soils being drained. Designers should always make sure that filters will be more permeable than soils being drained, never less permeable. If there is ever any doubt, the permeability of the filters should be verified by suitable laboratory or field tests.

Flow in the interior drain layer (zone 2) in the "chimney" drain in figure A-1a is vertically downward under a hydraulic gradient of approximately 1.0. Inasmuch as the required transmissibility T is equal to kt, and kt is equal to the discharge seepage quantity, Q divided by the hydraulic gradient, i, in the drain, its transmissibility must be at least Q/i or Q/1.0 or Q. But, in the outlet blanket, the hydraulic gradient is limited to an amount that will not allow excessive head to build up, and often must not exceed 2 or 3 percent. So the required transmissibility is equal to the discharge seepage quantity, Q, divided by 0.02 or 0.03 (typ.). (Note that the value of Q in the vertical part of the drain is different from the value of Q in the horizontal part of the drain. Subscripts such as "1" and "2" can be used if desired). Because of the small allowable hydraulic gradient in the outlet blanket and the usually greater seepage quantity, its transmissibility often must be at least 50 to 100 times that of the vertical part of the drain.

Very little water is likely to enter the drainage system from the downstream embankment zone, but the zone 3 transitions should be designed to meet the filter criteria so fine material will not enter and clog the drains from this side.

Figure A-1b shows a toe drain or trench drain with a pipe discharging the seepage to an exit. Surrounding the pipe is a zone of crushed rock or gravel (zone 2) designed to prevent piping of the surrounding zone of sand and gravel (zone 1) through the drain. Holes or slots in the pipe should be kept small enough to prevent the crushed rock or gravel from moving into the pipe. The sand and gravel (zone 1) is primarily a filter as it must hold all surrounding soils in place; however, it must have sufficient transmissibility to allow all incoming water to reach the coarse (No. 2 zone) without being choked off. Because this No. 1 zone is relatively large and provides rather large flow area, adequate permeability is usually not difficult to achieve. Nevertheless, in situations such as are shown here, because inadequate permeability can endanger projects, the transmissibility of both zones 1 and 2 should be checked by hydraulic calculations. The No. 2 zone is relatively small in size so its permeability must be increased sufficiently to compensate for its reduced inflow area.

Though the idea that the discharge capacity of drains must be great enough to remove all water needing to be removed without excessive head is not a new concept, hardly any designers have been consciously making calculations to establish minimum acceptable permeabilities in drains. Some major earth dams built in the past 20 to 30 years have had expensive, elaborate drainage systems that have provided practically no benefits because the drain zones contained so many fines that the discharge capabilities were as small as 1 percent or less of the levels needed. Careful application of the principles outlined in this appendix can virtually eliminate such errors. Making a hydraulic analysis, as discussed here, can be just as important as analyzing filter requirements, whenever discharge capacity of drains is important.

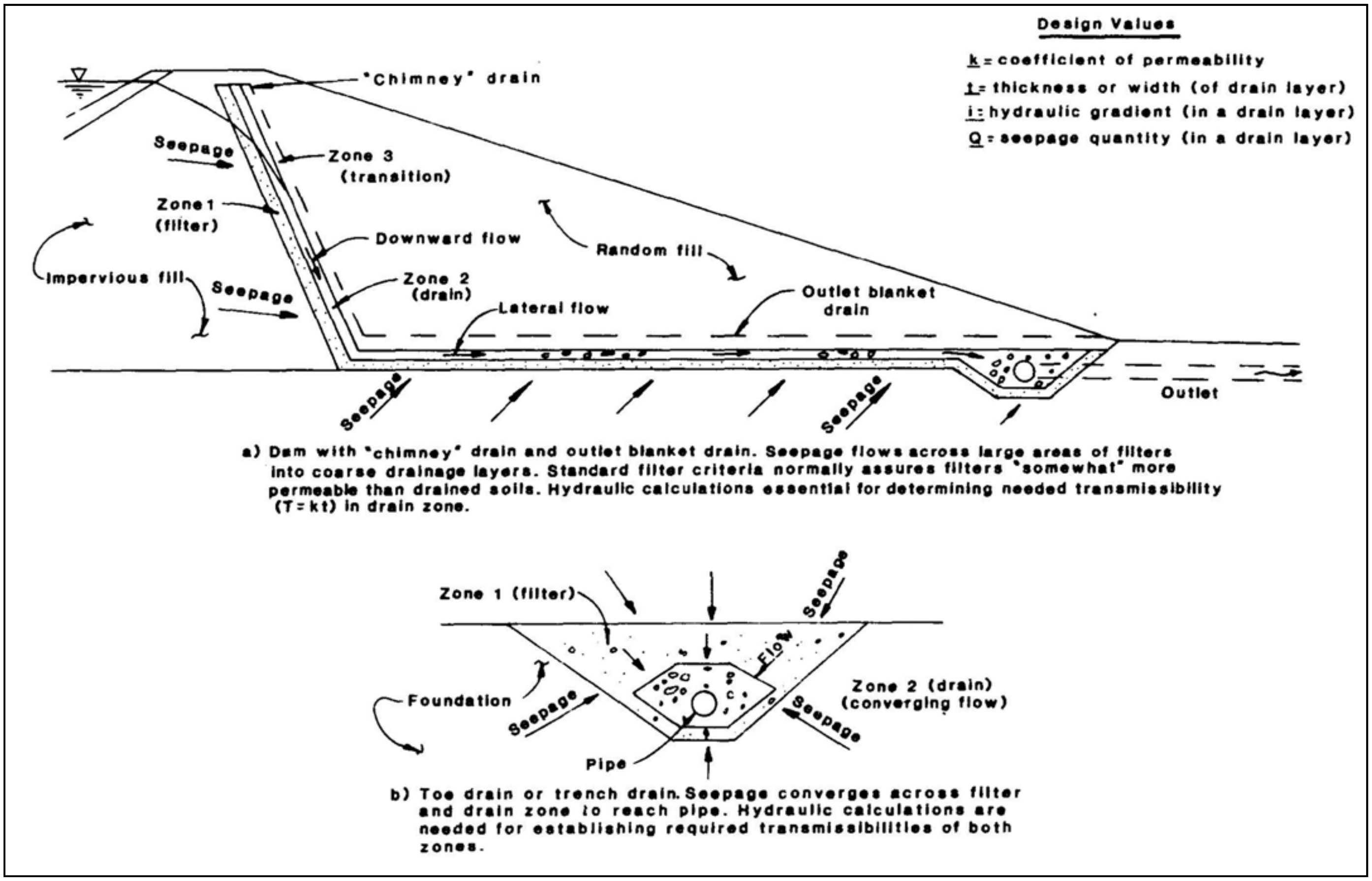

Figure A-1. Illustration of Filtering and Transmissibility Needs of Drains in Dams and Other Water Impounding Structures.

Appendix B

Geotextiles as Filters

by James R. Talbot

Appendix B

Geotextiles as Filters

Geotextiles in Embankment Dams

The following statement explains the current practice for using geotextiles in dams. The statement is taken from the July 2007 draft of "Geotextiles in Embankment Dams," *Status Report on the Use of Geotextiles in Embankment Dam Construction and Rehabilitation*:

> "Geotextiles are used in a variety of applications in embankment dam construction and rehabilitation. Although policy varies, most practitioners in the United States limit the use of geotextiles to locations where there is easy access for repair and replacement (shallow burial), or where the geotextile function is not critical to the safety of the dam should the geotextile fail to perform.
>
> In a limited number of cases, geotextiles have been used as deeply buried filters in dams in France, Germany, South Africa and a few other nations. Most notable, is a geotextile installed as a filter for Valcross Dam which has been successfully performing for over 35 years. These applications remain controversial and are not considered to be consistent with accepted engineering practice within the United States. Because geotextiles are prone to installation damage and have a potential for clogging, their reliability remains uncertain. Many organizations forbid their use in embankment dams in critical applications where poor performance could lead to failure of the dam or require costly repairs. Designers are cautioned to consider the potential problems associated with using a geotextile as a critical design element in a non-redundant manner deeply buried in a dam.
>
> It is the policy of the National Dam Safety Review Board that geotextiles should not be used in locations that are both critical to safety and inaccessible for replacement."

The authors of this manual concur with this policy, and additional discussion is provided in the following section.

Technical Evaluation of Geotextile Use in Filter/Drainage Systems for Dams

Sand and gravel filters have been tested in research studies simulating conditions within a dam and have been successfully used for many years as the main feature of filter/drainage systems to prevent piping and concentrated leak development in dams. This testing and extended successful use has demonstrated that the intended performance of these materials as filters for dams has been met. This is not the case with geotextiles as their "use" in embankment dams has been very limited. It is useful to consider the characteristics of sand filters in evaluating their success and to compare these characteristics with geotextiles for determining whether geotextiles can provide the same desirable performance.

Clean sand or sand and gravel mixtures act as a single-grain material. When there is very little or no binder material (fines such as silt and clay or a cementing agent) within the sand, it will flow to a soil boundary such as the side of a trench or a soil zone in an embankment and apply a positive pressure. The soil boundary acts as a barrier or containment for the sand as it is placed and compacted in a zone or trench. With no soil binder or cementing agent, the sand will shift or cave to maintain a continuous, homogeneous zone without cracks or openings as the dam settles or shifts during construction or during the first filling of the reservoir or an earthquake.

For intergranular seepage flow (seepage through soil with no cracks or defects), filters designed using current criteria were successful in testing studies for preventing any particles from detaching on the discharge face under high gradients. Apparently, there is some arching between the closely spaced contact points where the filter is in contact with the discharge face to prevent any movement of particles. Testing and experience shows that too coarse filters or other materials that do not support the discharge face with closely spaced contact points as seen in granular filters will not prevent soil particles from detaching when the seepage gradients exceed the critical gradient of the soil.

Geotextiles by themselves do not apply a positive pressure to the surface against which they are placed, as shown in figure B-1. Since the geotextile is a flexible fabric, it must have a material placed on the downstream side of the fabric to hold it against the discharge face. The material on the downstream side would need to be configured so that the contact points on the discharge face have similar spacing as the sand filter contact points. Grid materials or gravels placed on the downstream side of geotextiles will not provide the proper support to the discharge face, and contact points will be too far apart to prevent soil particle detachment. The geotextile will bulge out away from the soil surface between the points where gravel particles are in contact. If seepage gradients just upstream of the geotextile exceed the critical gradient for the base material in the dam, soil particles will be detached from the face and soil in suspension will arrive at the geotextile face. For geotextiles designed with an equivalent opening size (EOS) to meet the filtering requirements of the soil, the particles in suspension will be caught at the filter face in a layered filter cake with a very low permeability. The result will be clogging of the geotextile at all locations where high gradients exist (usually large segments of the drain). For fabrics with a larger EOS, the soil will pass on through the geotextile, and a piping feature will develop in the dam and progress toward failure.

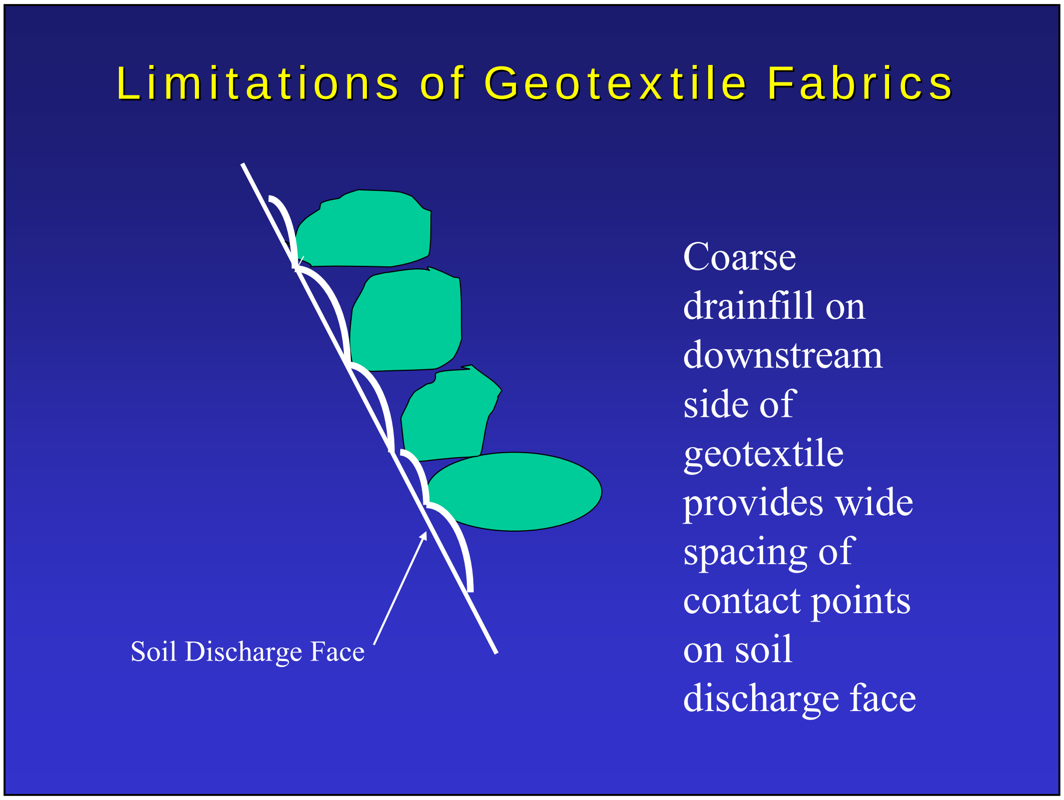

Figure B-1. Cross section of a base soil covered by a geotextile that is then covered by coarse gravel. Due to the voids in the gravel, the geotextile can "flex" into these voids, resulting in the loss of positive pressure on the base soil discharge face. Base soil particles can then detach and clog the geotextile.

This condition is exhibited in the gradient ratio test performed on geotextiles. In this test, water under pressure is applied to a soil specimen that has a geotextile placed under it. Pea gravel is used to support the geotextile. In most cases, at least some clogging and/or passage of soil material through the geotextile is reported in the test results. For the cases cited (Giroud, 2005) where geotextile use in dams has been successful (such as Valcros Dam), the seepage gradient may not be sufficient to cause removal of soil particles. Apparently no instrumentation has been installed to check the gradients in Valcros Dam or other dams cited where geotextiles have been successful, as these data are not given to support the performance. The only evidence given for these successes is that the dams appear to be performing well based on visual observation at the surface. It is possible that a given dam may be successful using a geotextile as the filter for the drainage system if the gradients remain low; however, most dams have the potential for high gradients that will cause particle detachment at the drain/soil interface. Also, piping/internal erosion is time dependent and may take more years to manifest itself visually.

There are many examples that demonstrate geotextiles do not prevent detachment of soil particles at the drain/soil interface when critical gradients are exceeded. Geotextiles used under riprap on the Tennessee-Tombigbee Waterway (U.S. Army Corps of Engineers, Engineer Technical Letter No. 1110-2-286, "Engineering and

Design Use of Geotextiles Under Riprap," dated 25 July 1984) showed that if the EOS was too small, clogging of the geotextile was a problem, causing buildup of seepage pressure under the riprap. This clogging could happen only if soil particles were detached with seepage water flowing out of the channel bank behind the geotextile. Using a larger EOS would allow the soil particles to pass through the geotextile, but would then cause a potential piping problem. This may not be serious for a channel with riprap, but would be very serious for an earth dam that retains a large reservoir of water serving as an essentially infinite source of seepage water to develop a piping failure condition.

Most studies and reports on using geotextiles for highway drainage work indicate that geotextiles either clog or allow soil particles to pass through. The most significant of these is Geosynthetics Research Institute paper (GRI-18, "Rapid Assessment of Geotextile Clogging Potential Using the Flexible Wall Gradient Ratio Test," by T.D. Bailey, M.D. Harney, and R.D. Holtz) presented at the Geo-Frontiers Conference, 2005. The results cited in this paper indicated that most tests showed some to major clogging while other tests showed particles passing through the geotextile. While this may be acceptable for highway drainage, it is not acceptable for earth dam drainage. Additional reports showing similar results are ASTM STP-1281, "Recent Developments in Geotextile Filters and Prefabricated Drainage Composites," and NCHRP Report 367, "Long-Term Performance of Geosynthetics in Drainage Applications."

Historical Use of Geotextiles in Earth Dam Construction

Geotextiles have been used as a separator between a sand filter and a coarse drainfill in downstream toe drains. As long as a properly designed sand filter is placed next to the soil where high gradients may exist, the soil fines will be prevented from migrating to the geotextile where they could clog it. A geotextile will perform a separation function if it is located between two dissimilar soils or between a soil and a manmade material to prevent the mixing of the two materials and not as a filter/drainage function. However, caution should still be exercised since even a small amount of fines in the filter can clog the geotextile. For this reason, this arrangement is not recommended.

There have also been successful drainage applications of geotextiles used in trench drains away from the dam where the potential for high gradients is very low. In these applications, the geotextile has been placed next to the soil in a trench with a coarse gravel drainfill inside the geotextile with or without a perforated or slotted drainpipe to carry the seepage water to a safe outlet. In these successful cases, the seepage passing through the soil does not have a gradient large enough to detach the soil particles where the geotextile is not in intimate contact with the soil between the gravel particles. It is recommended that this design not be used due to the difficulty in determining the gradient at the drain and especially estimating what the critical gradient will be.

Geotextiles have been used with mixed results as a separator between riprap and the upstream face of a dam. The drainage condition underneath the geotextile needs to be carefully considered. If drainage does not occur, which could be the result of clogging, rapid drawdown with no relief of pore pressure should be assumed for slope stability.

Geotextiles and other geosynthetics have been successfully used in a reinforcement function. A geosynthetic that allows stress transfer from a soil or adjacent material to the geosynthetic provides structural reinforcement. Thus, soil layers on slopes or within walls can be reinforced with geosynthetics specifically designed for taking stress to improve stability of slopes or walls. Geogrid are products specifically designed for this function, although woven and nonwoven geotextiles have been used where lower stress transfer is required.

Geotextiles have been used as a protection function between a geomembrane and a concrete or earth contact under the membrane. Heavy, nonwoven geotextiles are usually used for this purpose. These heavy geotextiles may also serve to drain water away from this contact in the planar direction of the geotextile.

Geotextiles are also used in erosion control. A myriad of products (many geocomposites of some type) all provide stabilization of the immediate soil surface to help control erosion and particle movement due to rainfall or water flow. These products may be used on dams, especially in spillways, and on the downstream slope for erosion protection.

Appendix C

Example—Filter Design

Appendix C

Example—Filter Design

Example Filter Grain Size Design

Background

In this example, a filter is required in the construction of a flood-protection parapet wall along the top of an existing dam as shown on figure C-1. The location of the filter material is such that the filter is not associated with a drainage feature but is functioning as a separation layer between the existing embankment dam core material and the aggregate base course[1] for asphalt paving on top of the dam in an area of potentially elevated seepage gradients directly behind the parapet wall during flood surcharge. The purpose of the filter (Zone 5) is to protect against piping failure caused by seepage flow under the wall during flood surcharge. Interface 1 is the boundary between the embankment dam core and the filter. Interface 2 is the contact between the filter and the aggregate base course.

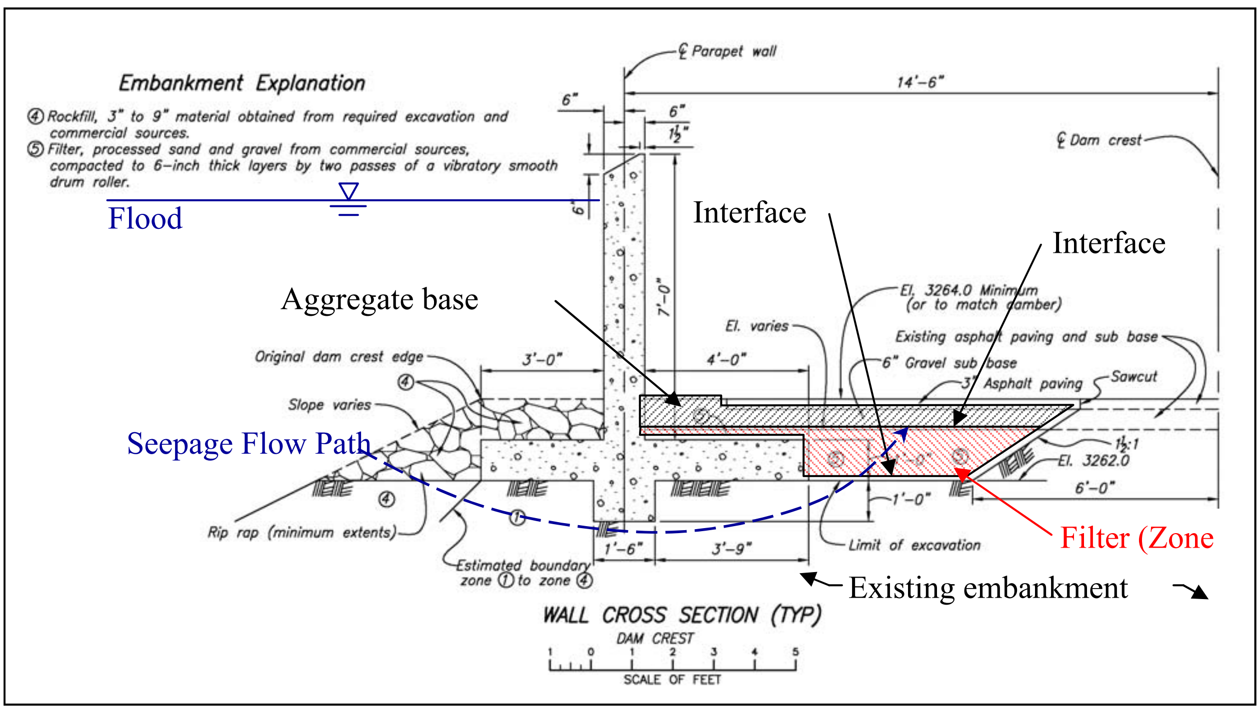

Figure C-1. Parapet wall cross section with location of Zone 5 filter and aggregate base course for paving.

[1] "Aggregate base course" is the standard naming convention for a pavement sub-base. This "base" should not be confused with the base soil used elsewhere in this example.

The following steps outline the procedure for specifying a filter material for this example. This example checks for filter compatibility at the two interfaces: (1) embankment dam core to Zone 5 filter, and (2) Zone 5 filter to aggregate base course.

Filter Check for Interface 1

Because the seepage during flood surcharge flows from the existing embankment dam core into the Zone 5 filter at Interface 1, the existing embankment dam core material functions as the base soil, and the Zone 5 material functions as the filter for this filter check.

Step 1: Plot the gradation curves of the base soil materials and determine if the base soils have dispersive clay content. The gradation curves for the existing embankment dam core material are plotted on figure C-2. The gradation for the five samples is fairly uniform, with the gradation curves falling within a 10-point band for percent passing along the entire gradation curve. The existing embankment dam is located in a region that is not known for dispersive clays.

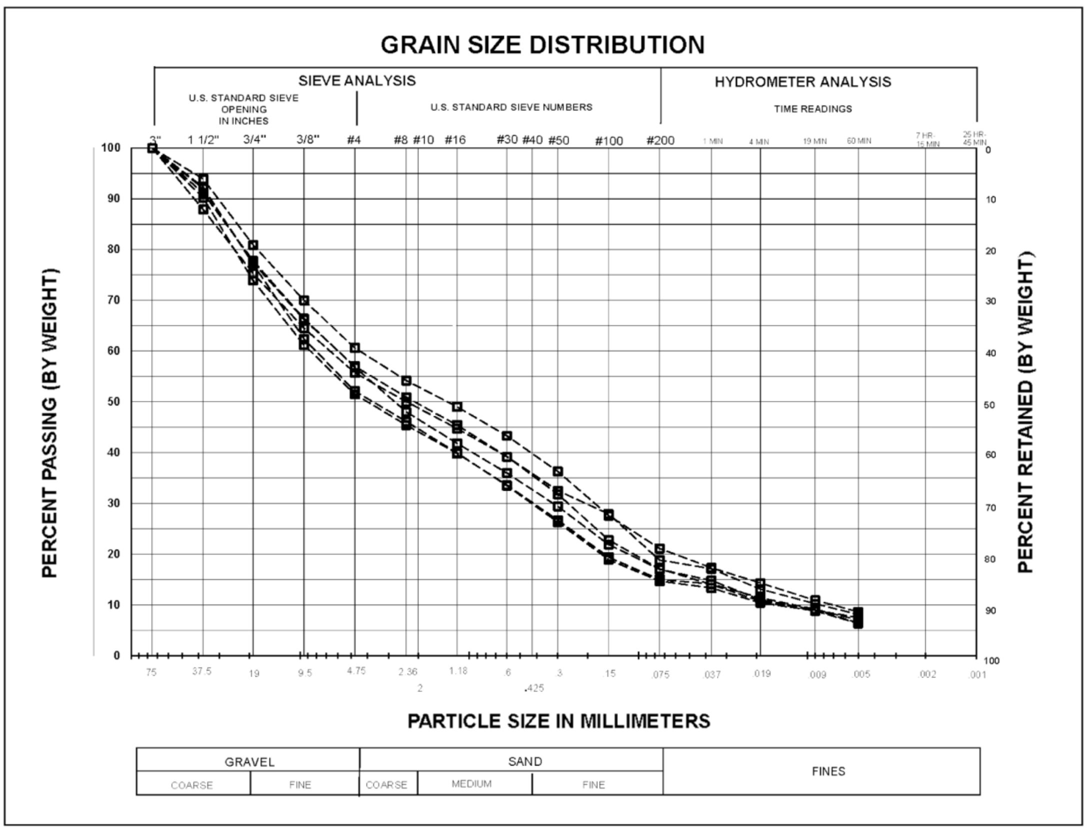

Figure C-2. Existing embankment dam core gradations before regrading.

Step 2: Determine if the base soil has particles larger than the No. 4 sieve and if the base soil is gap-graded or potentially subject to internal instability. The existing embankment dam core gradation curves include gravel contents in excess of 40 percent and fines contents of 15-20 percent. The soil is also broadly graded, with Cu = 398 to 811 (much greater than the limit of Cu < 6) and Cz = 0.64 to 1.57 (within the broadly graded range of 1 to 3). The gradation curves should be computationally regraded.

Step 3: Prepare Adjusted Regraded Gradation Curves for Base Soils. Each of the five gradation curves were regraded using the procedure described in chapter 5. The regraded gradation curves are shown on figure C-3.

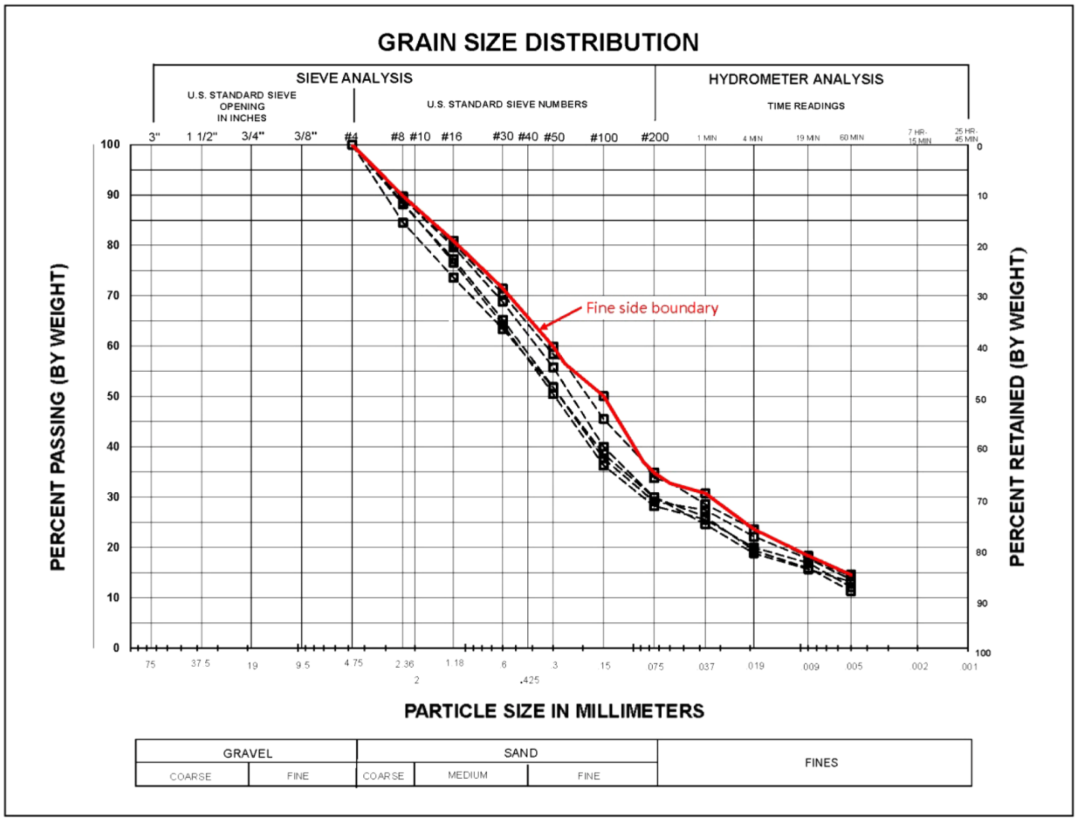

Figure C-3. Existing embankment dam core gradations after regrading.

Step 4: Determine the base category of the soil based on the percent passing the No. 200 sieve in accordance with table 4-1. The percent passing the No. 200 sieve for the regraded curves fall in the range of 28 to 35 percent, resulting in a base soil category of 3 for all five gradation curves. Based on the guidance provided in section 5.4.1.7 for base soil selection of earthfill materials with base soils that fall within one category for an existing dam (figure 4-14), the fine side boundary of the base soil gradation curves, as shown on figure C-3, should be used for filter design.

Step 5: Determine the maximum allowable D15F size to satisfy particle retention requirements in accordance with table 4-2. For base soil category 3, with a fines content of 35 percent and D85B = 1.71 millimeters (mm) from the fine side boundary of the existing embankment dam core gradation curves, the maximum D15F is calculated as:

$$(D_{15}F)_{max} = [(40\text{-}35)/(40\text{-}15)][(4)(1.71 \text{ mm})\text{-}0.7 \text{ mm}] + 0.7 \text{ mm} = 1.98 \text{ mm}$$

This value is plotted as filter control point A on figure C-4.

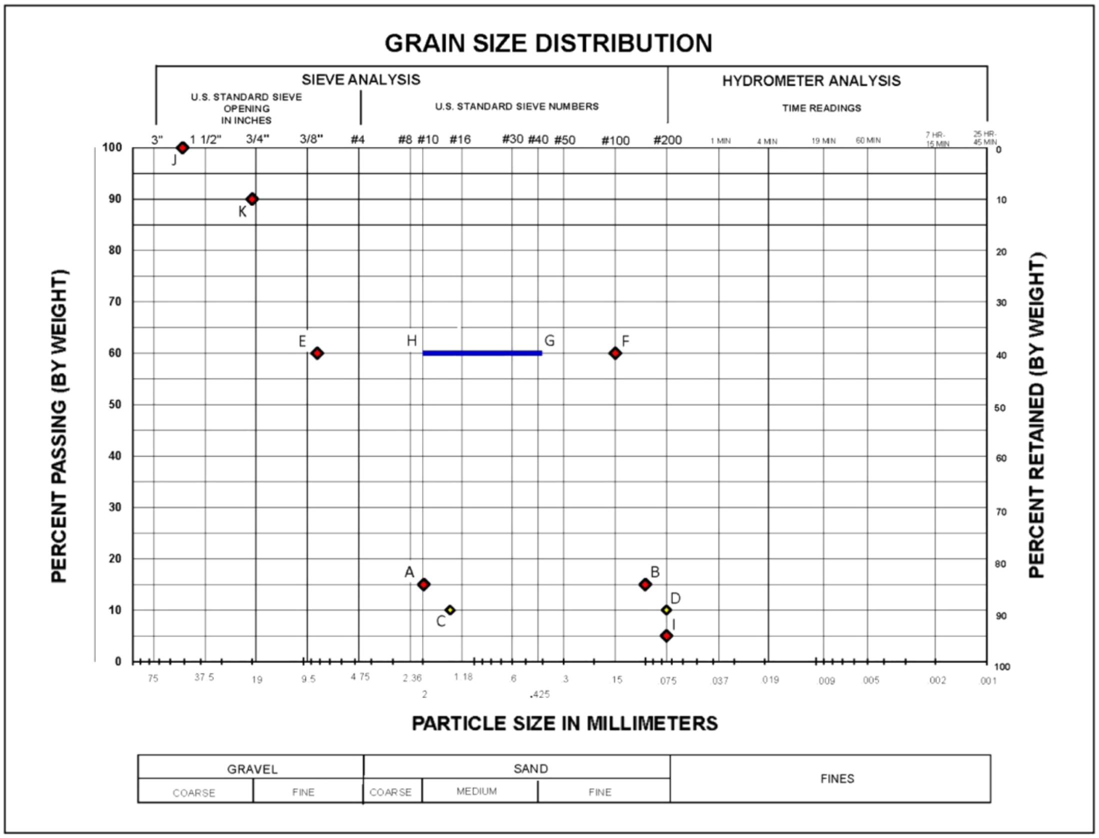

Figure C-4. Filter control points for Interface 1.

Step 6: Determine the minimum allowable D15F to satisfy permeability requirements. With $D_{15}B = 0.005$ mm from the fine side boundary of the existing embankment dam core gradation curves, the equation for the minimum allowable $D_{15}F$ gives:

$$(D_{15}F)_{min} = (5)(0.005 \text{ mm}) = 0.025 \text{ mm}$$

This values is less than the minimum value of 0.1 mm specified in the procedure, so the minimum $D_{15}F = 0.1$ mm. This value is plotted as point B on figure C-4.

Step 7: Determine the limits of $D_{60}F$ to limit the width of the filter band and possible gap-gradedness.

(a) Maximum D_{10} anchor point (point C):

C = A x 0.7 = (1.98 mm)(0.7) = 1.39 mm

(b) Minimum D_{10} anchor point (point D):

D = B x 0.7 = (0.1 mm)(0.7) = 0.07 mm, which is less than the minimum value of 0.75 mm

Because the calculated value of D is less than the minimum value of 0.75 mm provided in the guidelines, D = 0.075 mm

(c) Maximum D_{60} anchor point (point E):

E = C x 6 = (1.39 mm)(6) = 8.34 mm

(d) Minimum D_{60} anchor point (point F):

F = D x 2 = (0.075 mm)(2) = 0.15 mm

(e) The size of the sliding bar (points G & H[2]):

G >= 0.15 mm
H = G x 5

These values are plotted as points C through G on figure C-4.

Step 8: Determine the minimum D_5F and maximum $D_{100}F$ to limit the amount of fines and oversized material in accordance with table 4-3. For all base soil categories, $(D_5F)_{min}$ = 0.075 mm and $(D_{100}F)_{max}$ = 51 mm. These points are plotted as points I and J, respectively, on figure C-4.

Step 9: Determine the maximum $D_{90}F$ to limit segregation potential from table 4-4. For all base soil categories, with a minimum $D_{10}F$ = 0.075 mm, the maximum $D_{90}F$ = 20 mm. This point is plotted as point K on figure C-4.

Step 10: Determine the gradation band within the control limits. As a trial, the gradation band for C33 "concrete sand" is plotted on figure C-5, along with the filter control points from figure C-4 to determine if it falls within the control points.

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[2] In this example, a "horizontal sliding bar" is used the width of the gradation limits. This procedure is a variation of the method used by the Natural Resources Conservation Service in their filter design standard. The procedure presented in section 5.4.7 of this chapter uses a "vertical sliding bar." The 'vertical bar method' is presented later in this example. Both methods results in the same solution.

The band width defined by points G and H was slid between points E and F such that it coincides with the gradation band for C33 “concrete sand.” Because the gradation band for C33 “concrete sand” falls within all of the filter control points for Interface 1, C33 “concrete sand” can be used as the filter material for this interface.

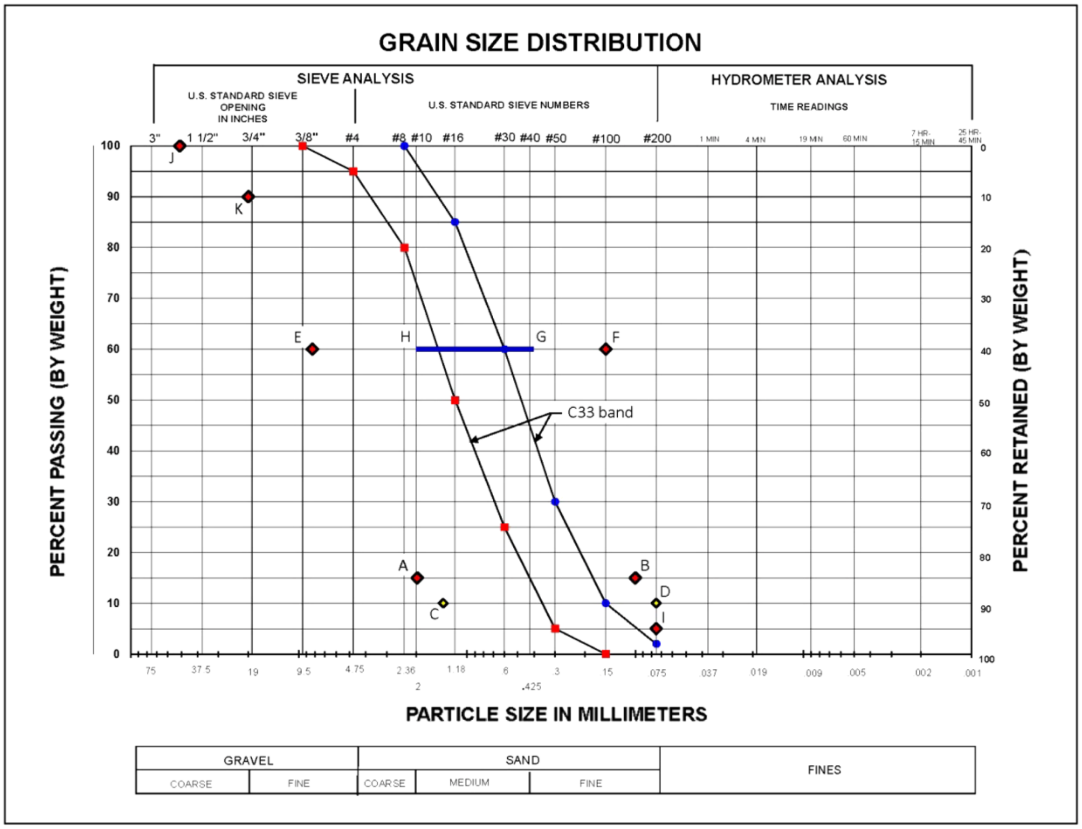

Figure C-5. Gradation for C33 “concrete sand” plotted with the filter control points for Interface 1.

Vertical Bar Method for Limiting Gap-Graded Gradation During Filter Design

The vertical bar method for controlling the width of the midportion of the gradation band is shown on figure C-6. This method uses filter design control points A, B, I, J, and K from figure C-4, with a sliding vertical band defined by points L and M, that cannot cross the line between points A and K and requires the filter gradation to be no greater than 35 percentage points vertically. The gradation band for C33 “concrete sand” is also plotted in figure C-6 to check its compatibility with the filter design criteria. Because the gradation band for C33 “concrete sand” falls within all of the filter control points for Interface 1, C33 “concrete sand” can be used as the filter material for this interface.

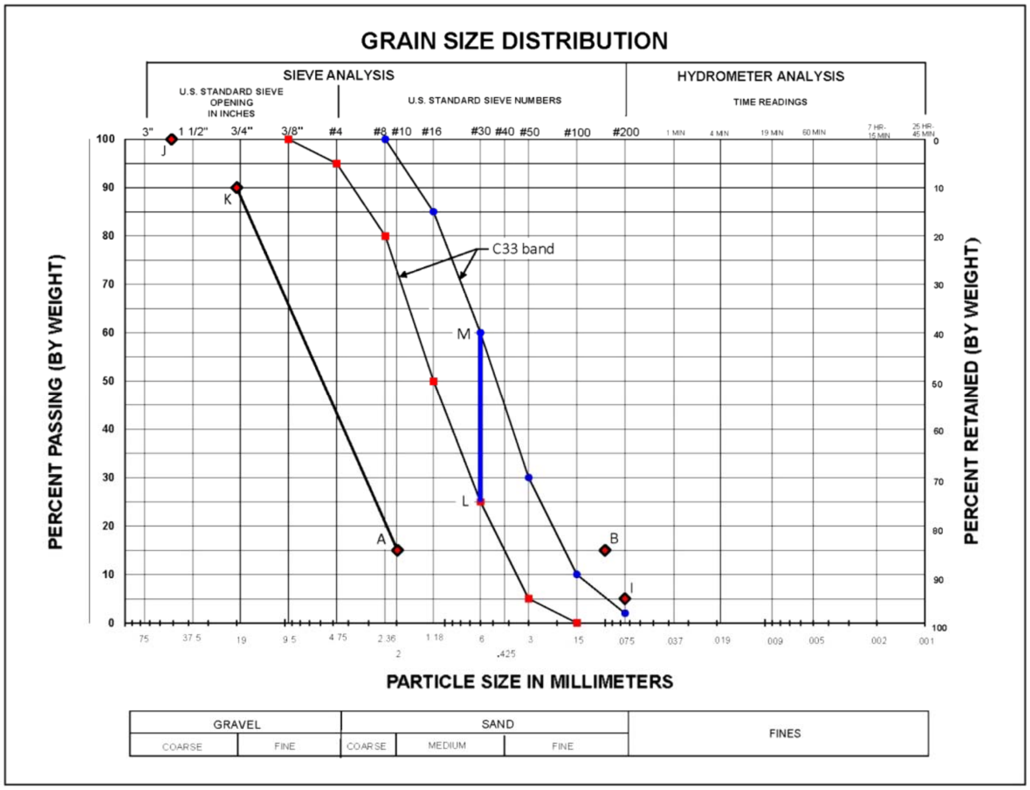

Figure C-6. Gradation for C33 "concrete sand" plotted with the filter control points for Interface 1 from alternate method.

Filter Check for Interface 2

Because the seepage during flood surcharge would flow from the Zone 5 filter material into the aggregate base course for the asphalt paving at Interface 2, the C33 "concrete sand" filter material functions as the base soil, and the aggregate base course functions as the filter for this filter check. The aggregate base course is an American Society for Testing and Materials (ASTM) D448 No. 467 aggregate. The gradation is illustrated on figure C-8.

Steps 1-3: The gradation range for the C33 "concrete sand," shown on figures C-4 and C-5, is fairly uniform and has less than 5 percent passing the No. 4 sieve. This material is not gap graded (Cu = 4 to 4.2 and Cz = 0.9 to 1.0). Therefore, the C33 gradations do not need to be regraded.

Step 4: The percent passing the No. 200 sieve for C33 "concrete sand" is less than 2 percent, resulting in a base soil category of 4. Based on the guidance provided in section 5.4.1 for base soil selection of earthfill materials with base soils that fall within one category, the fine side boundary should be used for filter design.

Step 5: For base soil category 4, with a $D_{85}B$ = 1.18 mm from the fine side boundary of the C33 gradation curves, the maximum $D_{15}F$ is calculated by:

$$(D_{15}F)_{max} = 4 \times D_{85}B = 4(1.18 \text{ mm}) = 4.72 \text{ mm}$$

This value is plotted as filter control point A on figure C-7.

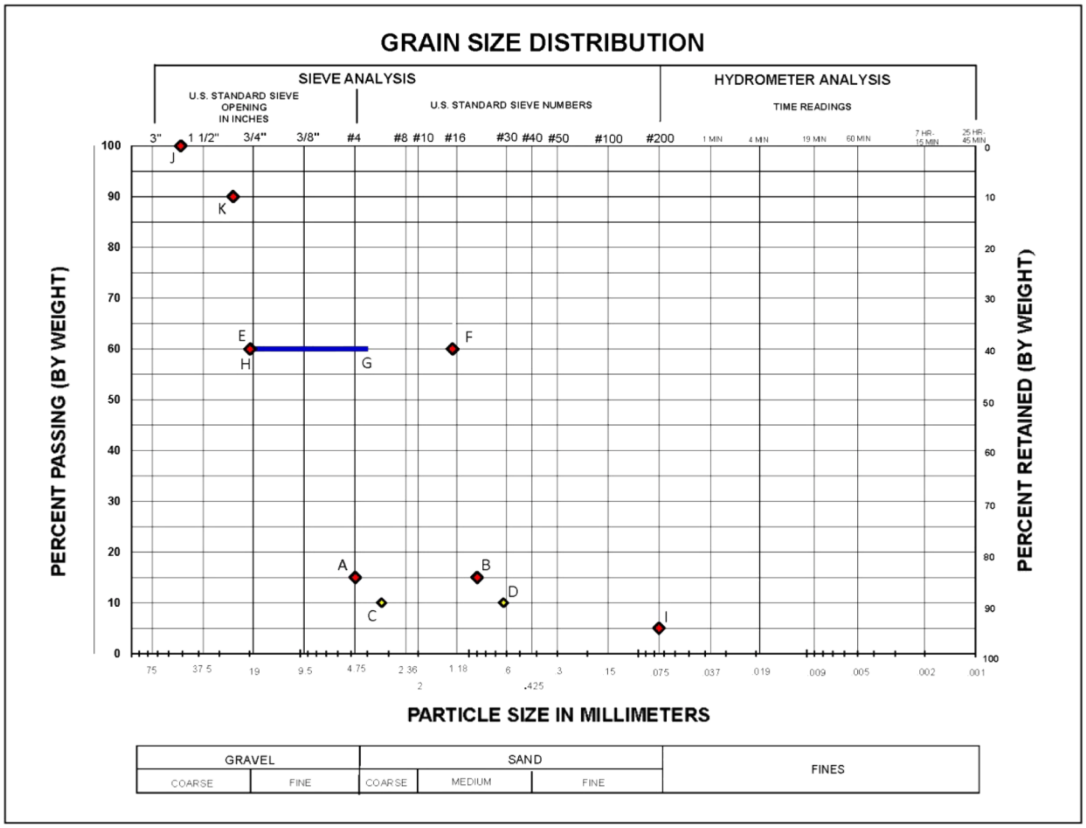

Figure C-7. Filter control points for Interface 2.

Step 6: With $D_{15}B = 0.18$ mm from the fine side boundary of the C33 gradation curves, the equation for the minimum allowable $D_{15}F$ gives:

$$(D_{15}F)_{min} = (5)(0.18 \text{ mm}) = 0.9 \text{ mm}$$

This value is plotted as point B on figure C-7.

Step 7: Find the horizontal sliding bar:

(a) Maximum D_{10} anchor point (point C):

$$C = A \times 0.7 = (4.72 \text{ mm})(0.7) = 3.30 \text{ mm}$$

(b) Minimum D_{10} anchor point (point D):

$$D = B \times 0.7 = (0.9 \text{ mm})(0.7) = 0.63 \text{ mm}$$

(c) Maximum D_{60} anchor point (point E):

$$E = C \times 6 = (3.30 \text{ mm})(6) = 19.8 \text{ mm}$$

(d) Minimum D_{60} anchor point (point F):

$$F = D \times 2 = (0.63 \text{ mm})(2) = 1.26 \text{ mm}$$

(e) The size of the sliding bar (points G and H):

G >= 0.15 mm
H = G x 5

These values are plotted as points C through G on figure C-7.

Step 8: For all base soil categories, (D5F)min = 0.075 mm and (D100F)max = 51 mm. These points are plotted as points I and J, respectively, on figure C-7.

Step 9: For all base soil categories, with a minimum D10F = 0.63 mm, the maximum D90F = 25 mm. This point is plotted as point K on figure C-7.

Step 10: ASTM D448 No. 467 is selected as a trial gradation. The gradation band for the No. 467 material is plotted on figure C-8, along with the filter control points from figure C-7 to determine if it falls within the control points.

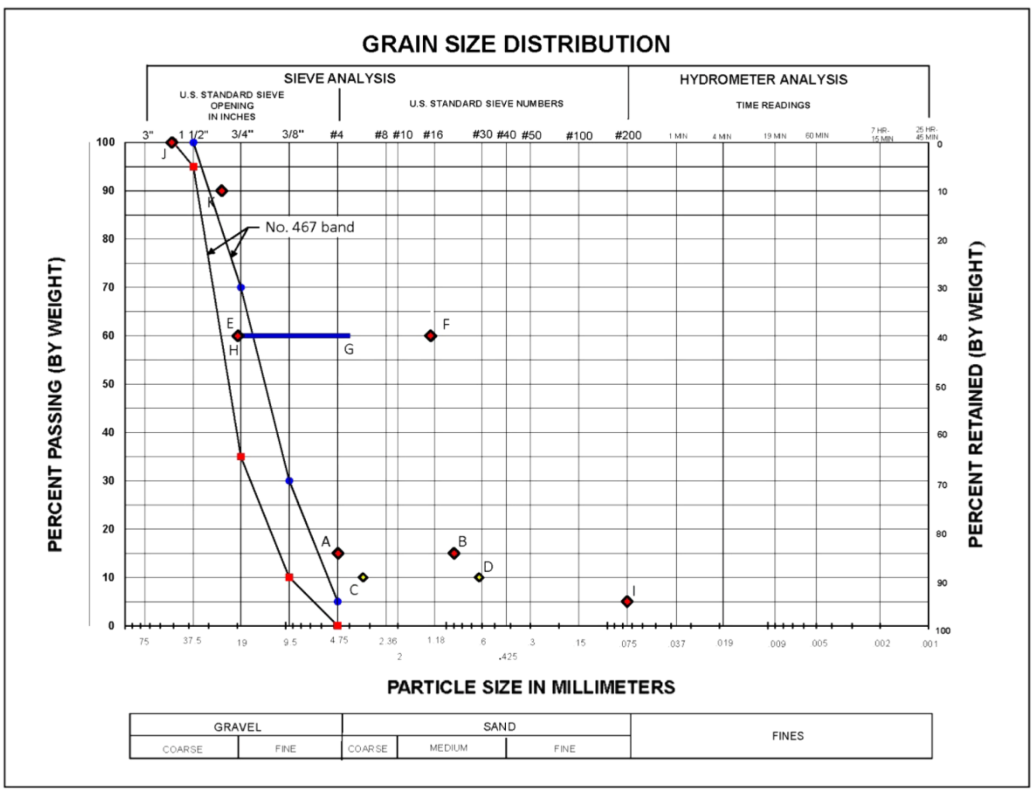

Figure C-8. Gradation for ASTM D448 No. 467 plotted with the filter control points for Interface 2.

Because the gradation band for the No. 467 material falls outside of the coarse side filter gradation control points (particle retention requirements) for the C33 "concrete sand," the filter design for this interface will be adjusted to emphasize permeability requirements. For this filter interface, the maximum $D_{15}F$ can be increased to $(D_{15}F)_{max} = 9 \times D_{85}B$, which will allow for particle rearrangement.[3] This is allowable because both the base soil (C33 "concrete sand") and the filter (ASTM D448 No. 467) are processed materials and grain size variability is minimized.

The adjusted maximum $D_{15}F$ (filter control point A):

$$(D_{15}F)_{max} = 9 \times D_{85}B = 9(1.18\text{ mm}) = 10.62\text{ mm}$$

The adjusted maximum D_{10} anchor point (point C):

$$C = A \times 0.7 = (10.62\text{ mm})(0.7) = 7.43\text{ mm}$$

The adjusted maximum D_{60} anchor point (point E):

$$E = C \times 6 = (7.43\text{ mm})(6) = 44.6\text{ mm}$$

In addition, the location of point K can be adjusted to consider a revised minimum $D_{10}F$ based on the No. 467 material being used as the filter material for this interface, rather than basing it on the filter control point D. For all base soil categories, with a minimum $D_{10}F = 5.5$ mm from the fine side boundary of the No. 467 gradation, the maximum $D_{90}F = 50$ mm.

The adjusted points A, C, E, and K are plotted, along with the other filter control points for Interface 2 and the gradation band for ASTM D448 No. 467, on figure C-9.

The band width defined by points G and H was slid between points E and F such that it coincides with the gradation band for No. 467. Because the gradation band for No. 467 falls within all of the filter control points for Interface 2, No. 467 is acceptable as the filter material for this interface.

[3] Also known as partial erosion, this is the erosion boundary between "no erosion" and "continuous erosion."

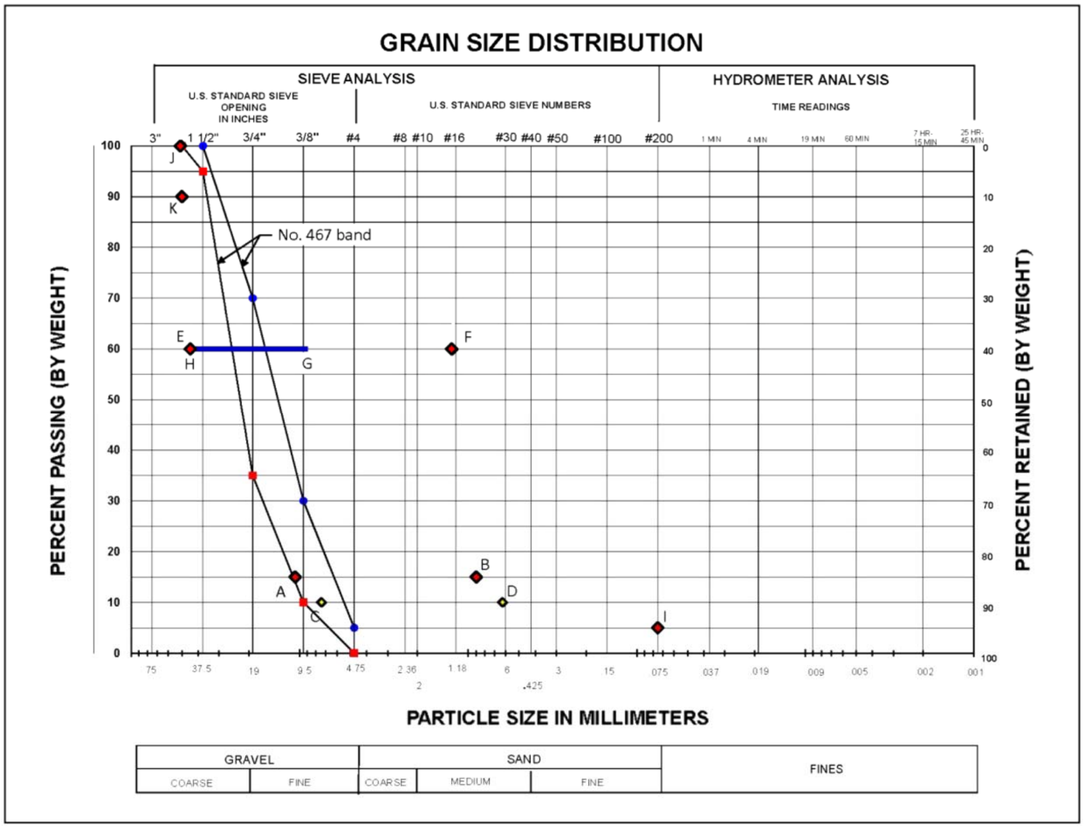

Figure C-9. Gradation for ATSM D448 No. 467 material plotted with modified control points for Interface 2 (allow for particle rearrangement)

Final Gradations

The regraded gradation curves for the existing embankment dam core material are plotted together with the gradation bands for the C33 "concrete sand" for the Zone 5 filter and the ASTM D448 No. 467 aggregate base course for paving on figure C-10.

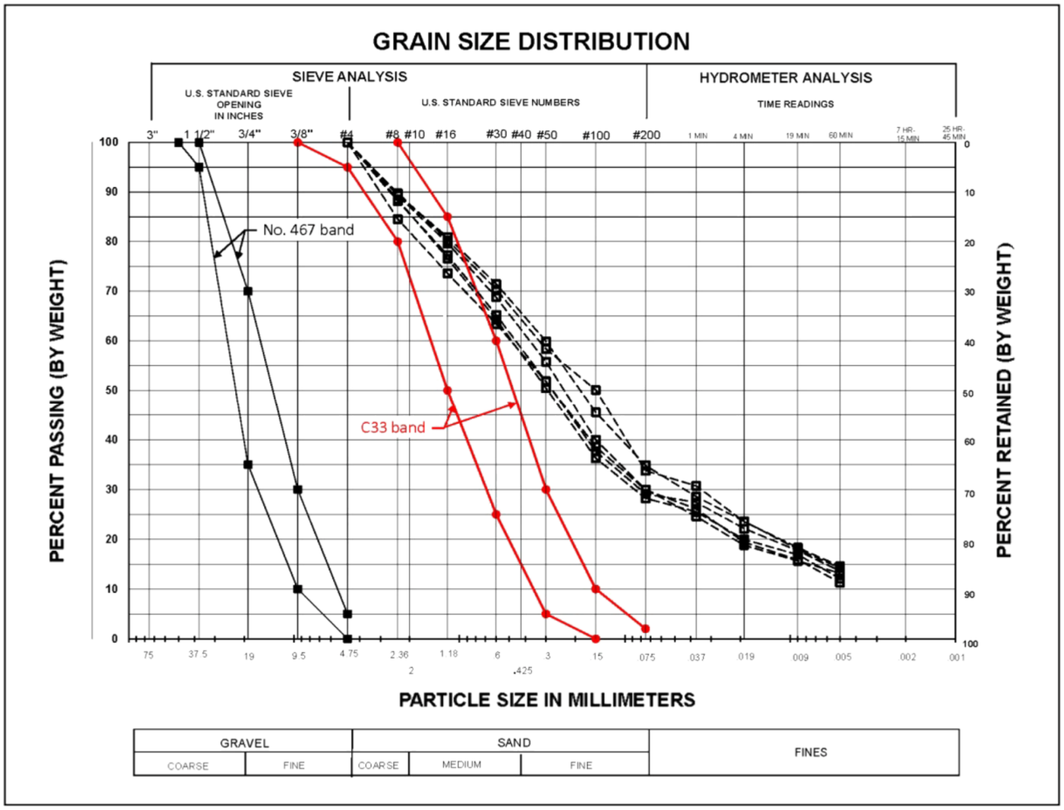

Figure C-10. Gradations for regraded existing embankment dam core material, C33 "concrete sand" (Zone 5 filter), and ASTM D448 No. 467 (aggregate base course).

Note: The pavement is impervious and will impede flow out of the base material. Therefore, sufficient outlet at the downstream side of the pavement is provided to relive uplift pressures. Otherwise, the pavement will be lifted and damaged.

Appendix D

Example—Inadequate Filter and Drain Geometry

Appendix D

Example – Inadequate Filter and Drain Geometry

As part of a safety of dams modification to a 100-year-old dam, a large toe drain system was added to address deficiencies associated with pervasive seepage through the foundation. Due to the size of the repair, and in the interest of keeping costs low, a modest cross section was used as shown in figure D-1.

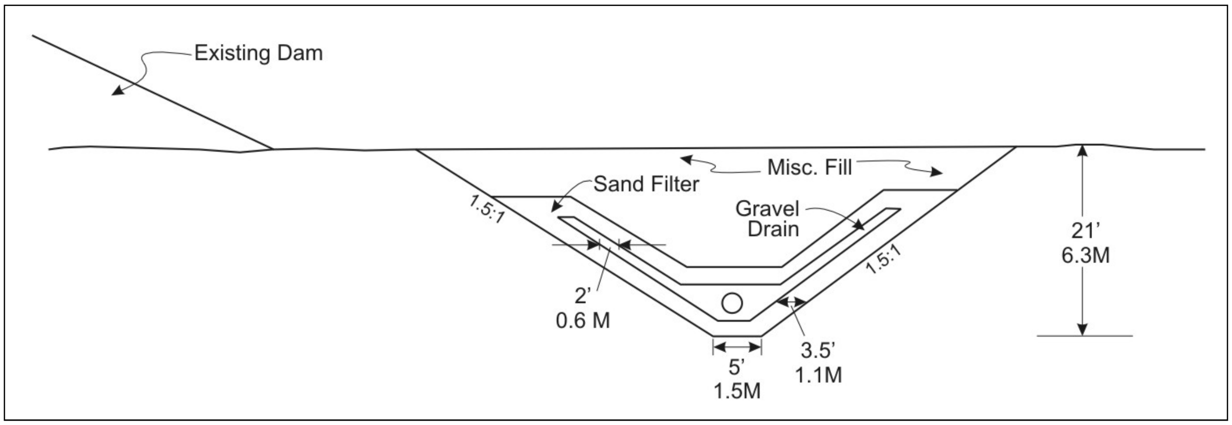

Figure D-1. Toe drain configuration at the end of construction.

Upon first filling, silt and sand were detected in the sedimentation traps that were included in the inspection wells added during the modification. The rate at which material was collecting in the sedimentation traps, along with the cloudy color of the collected flow, indicated that the new drainage system had failed in some way. A forensic investigation was undertaken in the form of removing portions of the new drain system. That investigation led to the following understanding of what had happened.

As shown on figure D-2, the filter layer against the foundation was found to be less than the specified width and, in some places, was completely missing. It has been speculated that when the trackhoe rotated, the back of the cab would run into previously placed filter material. It is also possible that equipment travel along the trench, as well as entering and exiting the trench, could have led to removal of the filter layer against the foundation. Construction was performed in the winter months while the reservoir was low, and the limited hours of daylight resulted in some construction at night. While continuous onsite construction inspection was performed by the owner, the damage was not detected by staff.

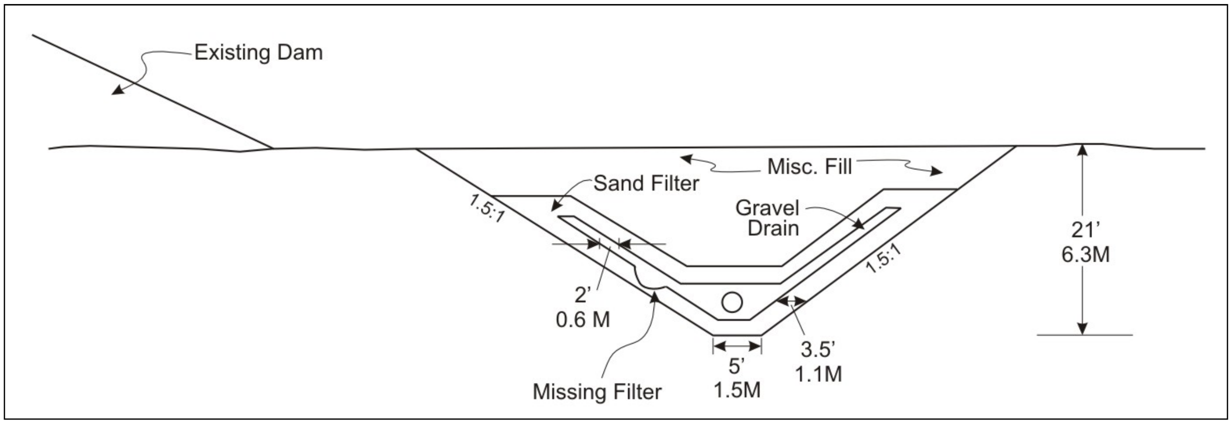

Figure D-2. Area of possible filter damage.

Since the gravel drain was in direct contact with the foundation in some places and the foundation contains silts, sands, and gravels, filter compatibility was not met. Therefore, silt and sand were able to erode (pipe) into the gravel drain as shown on figure D-3.

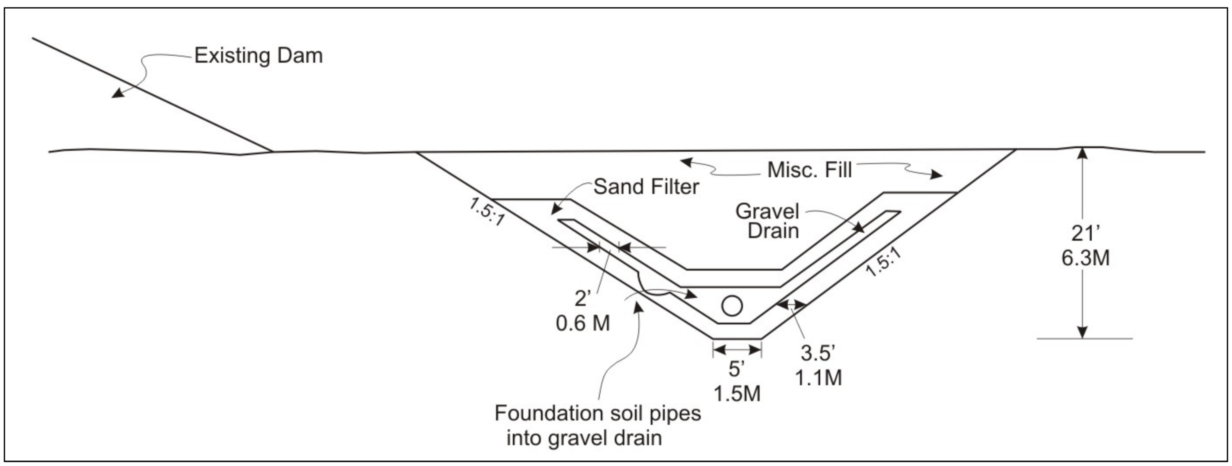

Figure D-3. Piping of foundation soil into gravel drain.

Material transport continued through the gravel drain and through the perforations in the drainage pipe. The flow in the pipe then carried the material to the sediment trap, where it was identified during refill monitoring. Material transfer into the pipe is illustrated on figure D-4.

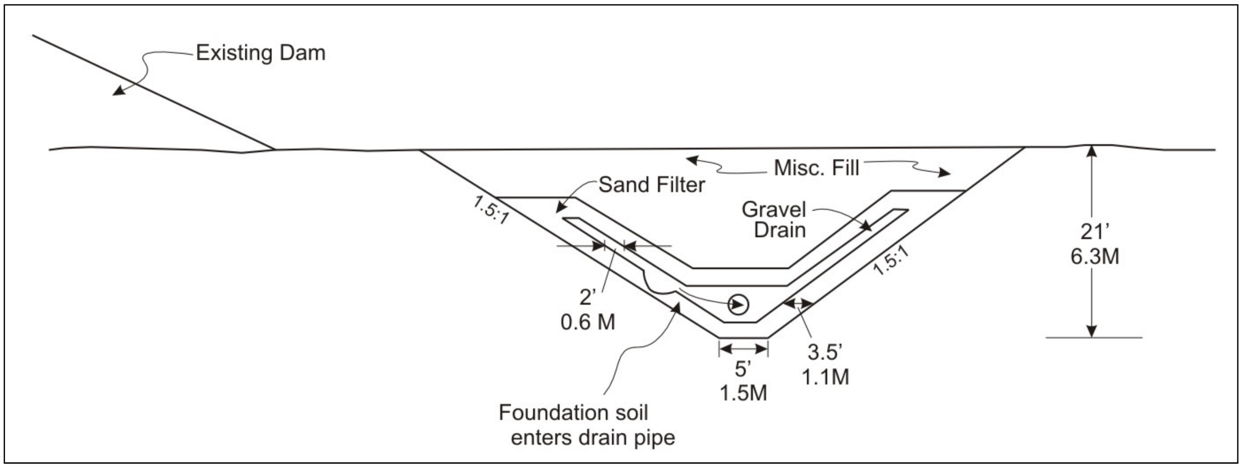

Figure D-4. Foundation soil passes through gravel drain and enters drainpipe.

Figure D-5 illustrates the problems with the toe drain design. The narrow bottom width made it impractical for commonly available construction equipment to work in the bottom of the trench. The 21-foot depth made it impractical to work from the top to place initial lifts in the bottom of the trench. Trenches should always be sized so equipment can work from inside the trench and not from the top. Relatively steep side slopes were used and, while material could be placed and compacted on this slope, traffic up and down the slope would damage the surface. Lastly, narrow filter and gravel drain zones were used that were difficult to place and prone to damage.

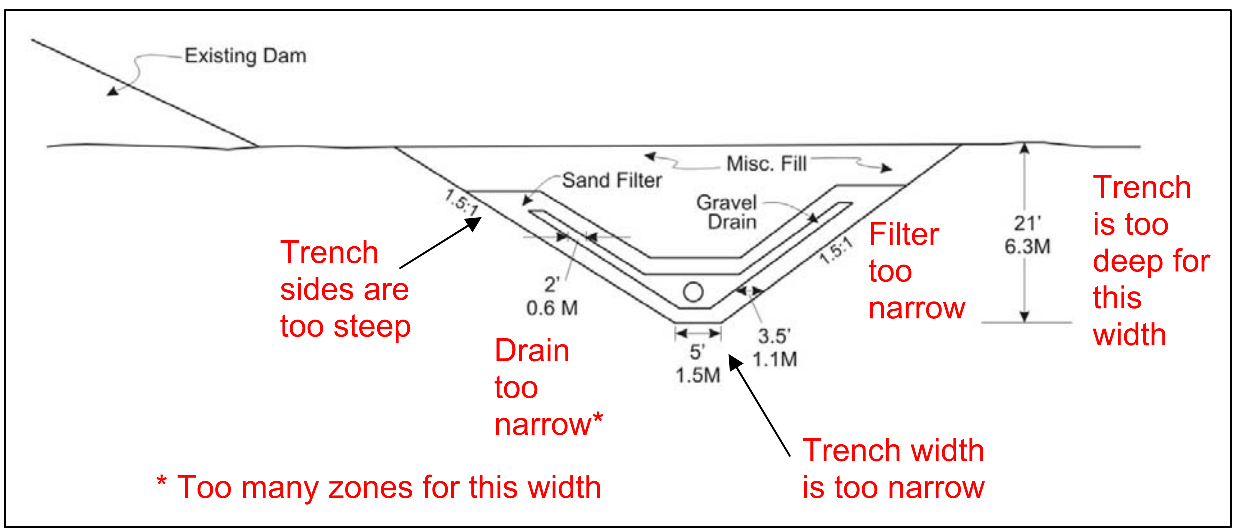

Figure D-5. Poor toe drain design elements.

Appendix E

Toe Drain Access Features

Appendix E

Toe Drain Access Features

Types of Access Features

Inspection wells provide access, sediments trap, and flow measurement features while joining two drain segments. They are the most costly of the ways to access a toe drain, with price ranging from $50,000 for a shallow, small diameter well to $75,000 for deeper, larger diameter wells with mechanical ventilation and lighting. Access at the upstream end (relative to flow in the pipe) of a toe drain can be achieved by an end access which is less costly than an inspection well (IW). These features are commonly referred to as cleanouts, end access points, or end sweeps. In a similar manner, lateral access points can be used for intermediate access between IWs and end access points for very long drain segments. Sedimentation traps and flow measurement are not possible with lateral sweeps.

Inspection Wells

The first component of an IW is the square base slab as shown in figure E-1. Reinforced concrete is used which can be either cast in place or a precast product. Slabs larger than 14 feet may be difficult to transport over the road, so cast in place construction would have to be used. The size of the base is dependent on the size of the risers described in the next section. The base should extend beyond the outside diameter of the riser by no less than 6 inches. (Example: a 10-foot-diameter riser would have an 11-foot-square base slab). Bearing capacity of the IW foundation is not an issue since the weight of the soil replaced by the volume of the IW results in a condition similar to a floating foundation.

The next components of the IW are the risers as shown on figure E-1. The risers are precast concrete rings (sewer pipe) 8, 10, or 12 feet in diameter. The size (diameter) of the riser is dependent on the expected flow through the well. Larger flows require a larger structure in order to accommodate the sediment trap and flow measurement device. Smaller flows can be measured by a weir, while larger flows will require a flume, which itself will require a larger diameter well. The height of the IW is dependent on the invert elevation of the drain and the final grade of the ground surface. The riser should be set no less than 1 foot above final grade. When the ground surface is sloping, the IW should be no less than 1 foot above the highest point on the slope/riser contact. Risers typically come in 4- to 8-foot lengths, and this determines the number of risers needed. Typically, the precast concrete manufacturer will determine the length of the individual segments given the total height required. Risers should be built in accordance with American Society for Testing and Materials (ASTM) C 478. Interlocking joints should be used between risers, and these joints should be sealed for water tightness meeting the requirements of ASTM C 920 (Sikaflex or equivalent). The bottom face of the bottom riser and the top face of the top riser should have flat surfaces as butt joints are used against the base and lid. These surfaces should also be sealed. Finally, a precast concrete lid is placed on top of the IW. Lid thickness is determined by the precast concrete manufacturer and is dependent on the well diameter and prescribed loads. Typically, in dam applications, vehicle loading is not required; however, if the IW is situated such that it is possible that a vehicle could pass over the IW, intentionally or not, HS-20 loading can be specified.

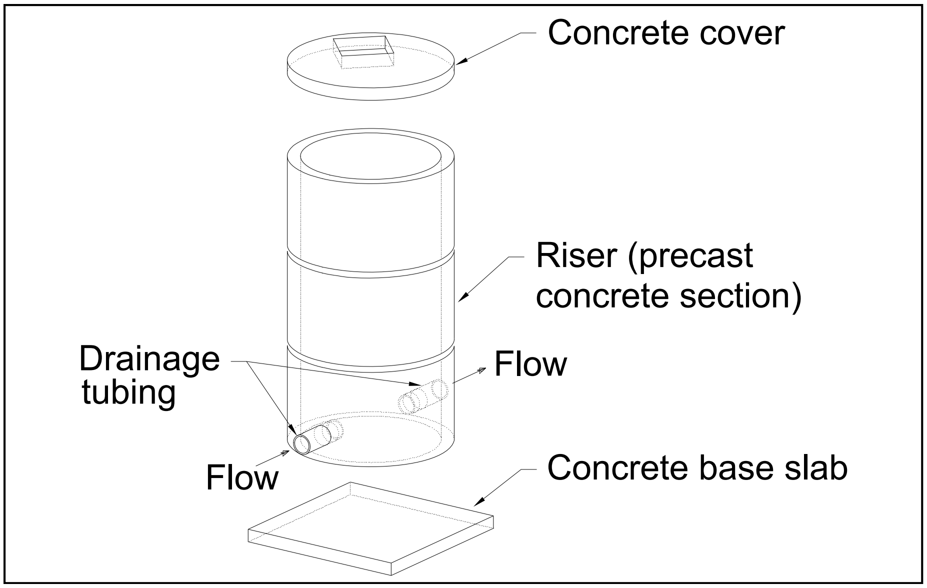

Figure E-1. Isometric view of inspection well basic components.

The bottom of the inspection well is separated into several bays. Divider walls are used to make these bays. The number of bays depends on the number of inlet and outlet pipes and the required flow measurements. The walls should be constructed out of metal, which will offer flexibility if changes are required at a later date. The upstream bay serves as the sediment trap and will also act as a quieting pool prior to flow passing through the weir or flume. Depending on the amount of flow entering this bay, a baffle may be needed to aid in quieting the flow. The bottom of this bay should be painted white with waterproof paint to aid in the detection of sediment in the bottom of the bay. The flow then passes through the measurement device consisting of a flume or weir. While weirs are more economical and require less space, they can be difficult to meet the approach requirements for quiet flow. Flumes typically are a better flow measurement scheme for inspection wells because they produce more consistent readings through a larger flow range. Downstream of the weir/flume is the discharge bay, which has no special requirements. As mentioned previously, the number of inlet and outlet pipes is dependent on the overall drain system layout. The simplest arrangement is one pipe in and one pipe out. Figure E-2 illustrates the basic components for the bottom of an IW.

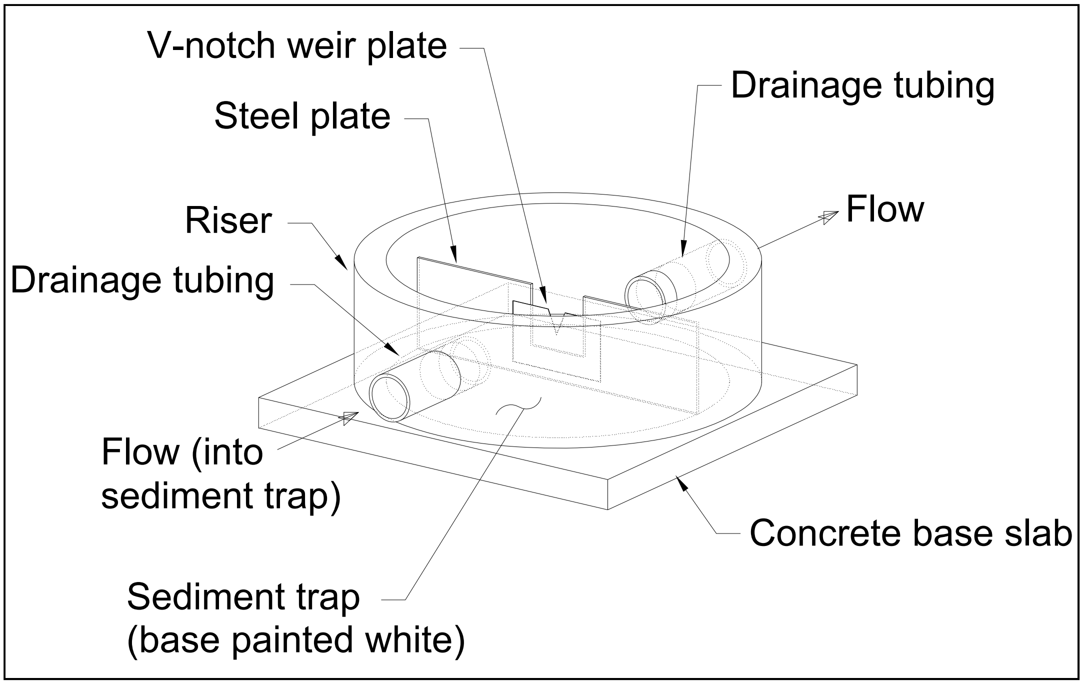

Figure E-2. Components in the bottom of a typical inspection well. Optional baffle at the end of the inlet pipe is not shown.

In order for the measurement device to work, a head drop is required through the IW. The drop should be no less than one pipe diameter of the largest pipe penetrating the well. As an example, the invert of a 12-inch inlet pipe should be at least 12 inches higher than the invert of a 12-inch outlet pipe. The invert of the measurement device should be set above the spring line of the discharge pipe assuming that the discharge pipe is not expected to flow full. Note that this arrangement can lead to "flooding" of the inlet pipe (the device backs up flow into the inlet pipe). To avoid this condition, the inlet pipe would have to be set above the expected flow depth through the device. The designer should be aware that to meet the head drop requirements through the inspection well, the grade of the inlet and outlet drain segments may differ by more than 1 foot (i.e., it is not possible to "insert" the IW into a constant grade invert from one segment to the next). Large changes in elevation through IWs can be problematic at sites with little topographic relief, and flooding of the inlet or discharge pipe might not be avoidable at all times.

Access in and out of the IW is by ladder. To prevent fall-type injuries, a safety ladder (safety rail) or landings should be used. Landings are constructed from metal grating at intervals prescribed by the applicable safety standard. Note that adequate free space should be left at the landings so that equipment in the bottom of the well can be removed and replaced. At the top of the ladder, an extendable grab bar (Ladder Up or equivalent) is required to assist workers in passing through the door. Figure E-3 illustrates a typical ladder and associated safety features.

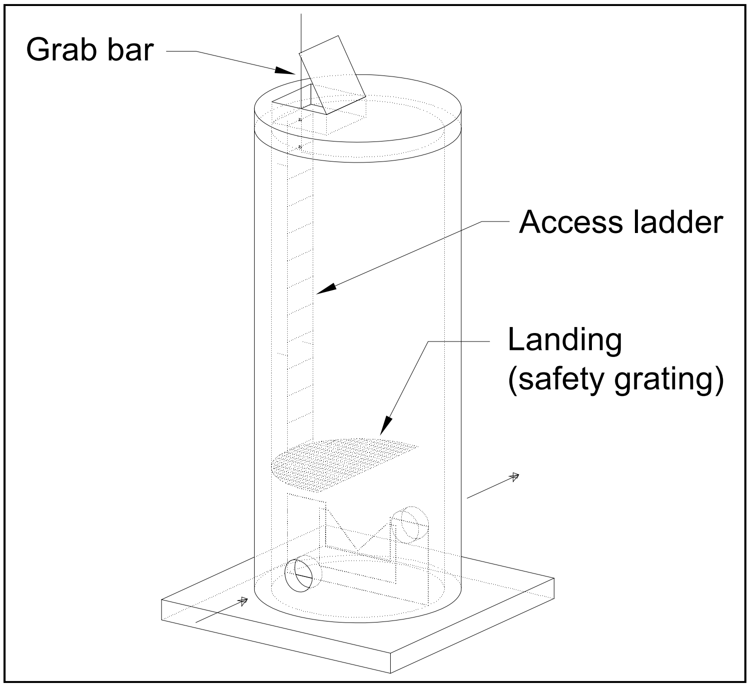

Figure E-3. Typical ladder and associated safety features.

Ventilation for the IW can be passive or active (the passive system is less costly). Client or safety requirements will dictate which type of system to use. The passive system consists of a vent tube, typically 8 inches in diameter from near the bottom of the well, through the lid, and terminated with a 180-degree (º) bend. This arrangement is also known as a J-vent due to its shape. Note that when passive systems are used, air monitoring is required because IWs are considered confined space.

The active type of ventilation has the same J-vent arrangement but with an inline fan added into the pipe near the bottom of the IW. Details of sizing the fan and on/off switching to the door are beyond the scope of this chapter. A typical J-vent is shown in figure E-4.

Electrical power is an optional feature for IWs. If active ventilation is needed, it will be required. When power is used, lighting can be added to the interior of the well, as well as power outlets for power tools, etc.

Outside of the IW, special attention to the backfill is required. If the backfill arrangement around the toe drain (filter and gravel envelope) was duplicated around the IW, this would allow flow in the filter and drain (flow parallel to the toe drain alignment) to not enter the pipe and bypass the flow measurement device. For this reason, an "underground dam" is used to force water into the pipe and through the measurement device. The dam consists of finer grain material that encapsulates the IW. Nonperforated pipe is used through the dam backfill. Figure E-5 illustrates this arrangement.

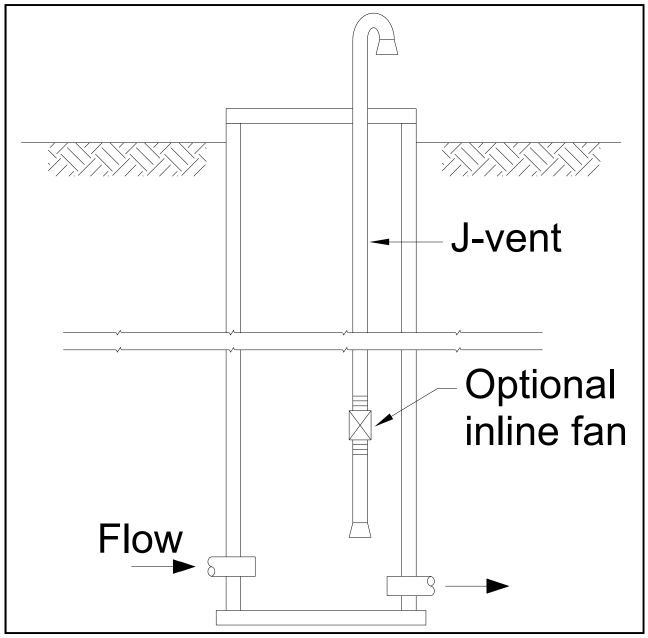

Figure E-4. Typical inspection well ventilation.

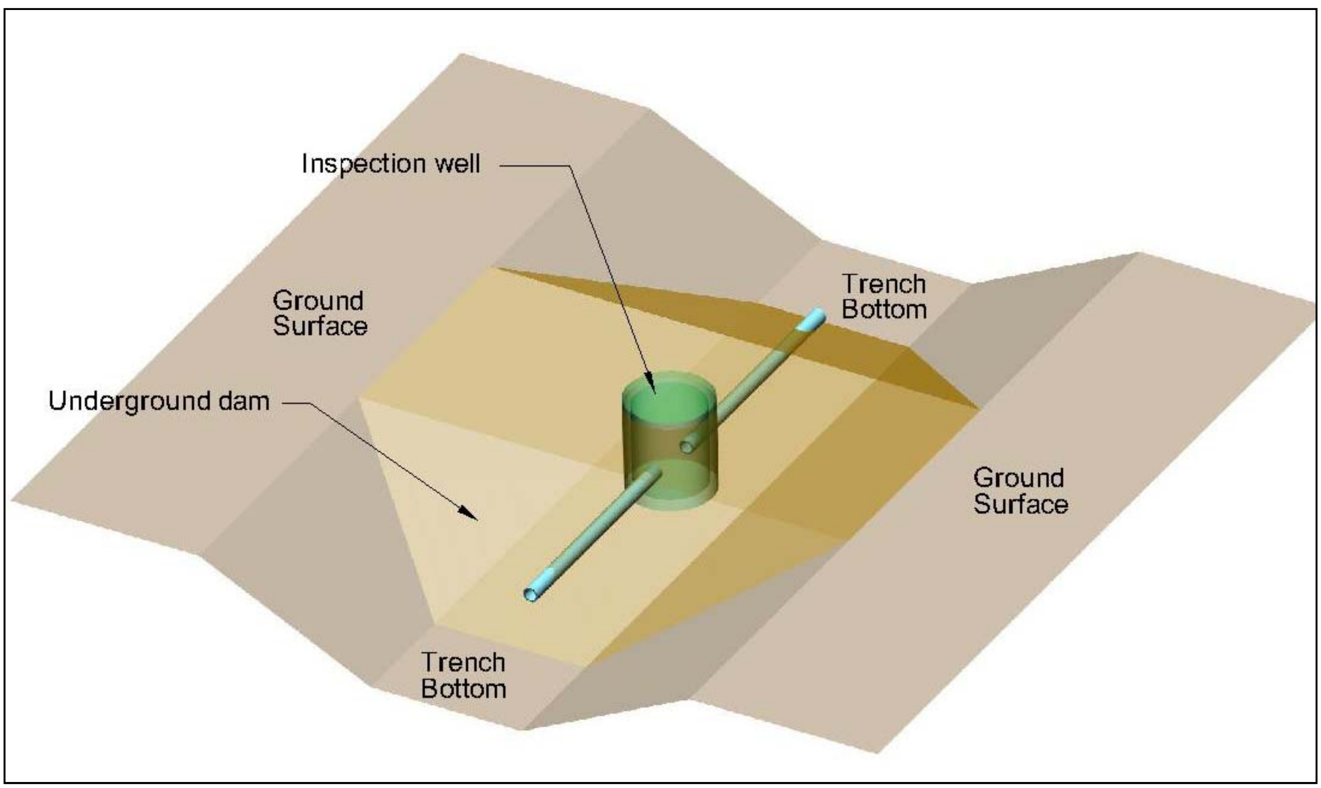

Figure E-5. Isometric view of an underground dam around an IW.

End Access

Access to the end of a drain system can be made by bringing the drainage pipe to the ground surface (also known as a sweep). This can be done by a series of off-the-shelf fittings. For a pipe exiting the ground at a 45° angle, two 22.5° fittings can be used. Angles greater than 22.5° should not be used due to difficulty in getting cameras and cleaning tools past these sharper bends. At the connection between the drain pipe and sweep, the pipe should transition from perforated to nonperforated since the sweep will be backfilled with finer grained material. This material acts as a barrier to prevent surface water from entering the drain system along the sweep, similar to impervious caps that are placed over toe drains. Near the ground surface, the drainage pipe should be protected, typically with a corrugated metal pipe (CMP). The drain pipe is centered inside the CMP pipe with granular backfill. This protective shroud is embedded in the ground about 10 feet and does not require concrete backfill. A lockable lid is fitted to the CMP to protect access into the drain system. The components of these features are illustrated in figure E-6.

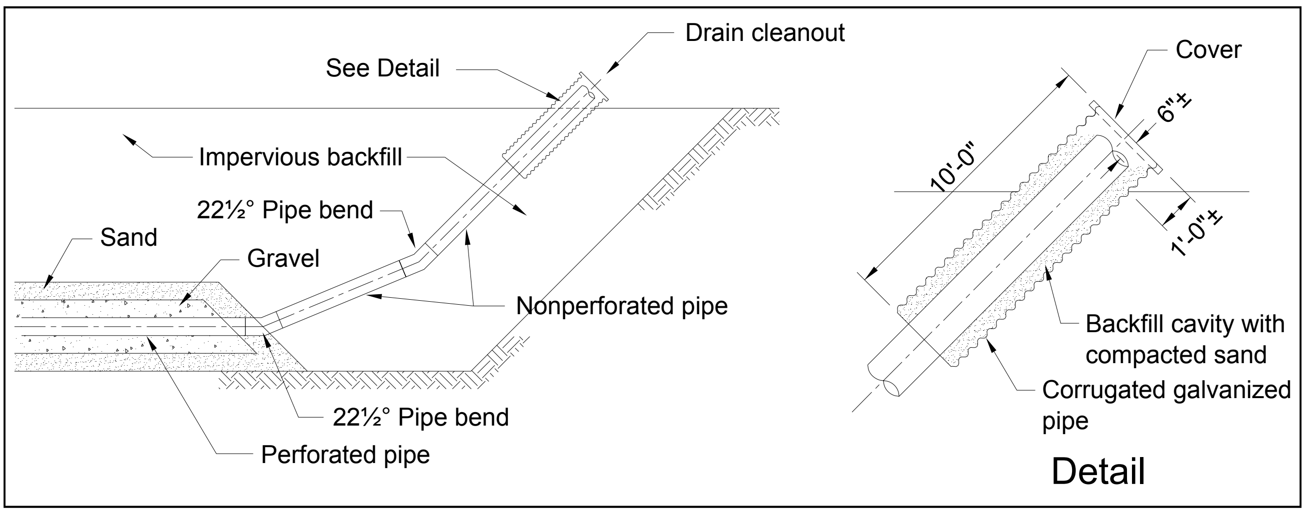

Figure E-6. Toe drain end access features.

Lateral Access

Similar to the end access feature described above, access to long drain segments can be achieved by adding a lateral access. This type of access includes a "Y" fitting inserted into the main toe drain line which only allows one-way access. A short piece of nonperforated pipe is installed into the lateral portion of the 'Y'. The 'Y' fitting adjusts the alignment in the horizontal direction. Next, a pipe bend is added to adjust the alignment in the vertical direction. Another short nonperforated piece of pipe is added, followed by another pipe bend. These two pipe bends will bring the pipe out of the ground in the vertical plane at a 45° angle. The access is then finished the same as the detail shown in figure E-6. An isometric view of a typical lateral access and its components is shown in figure E-7.

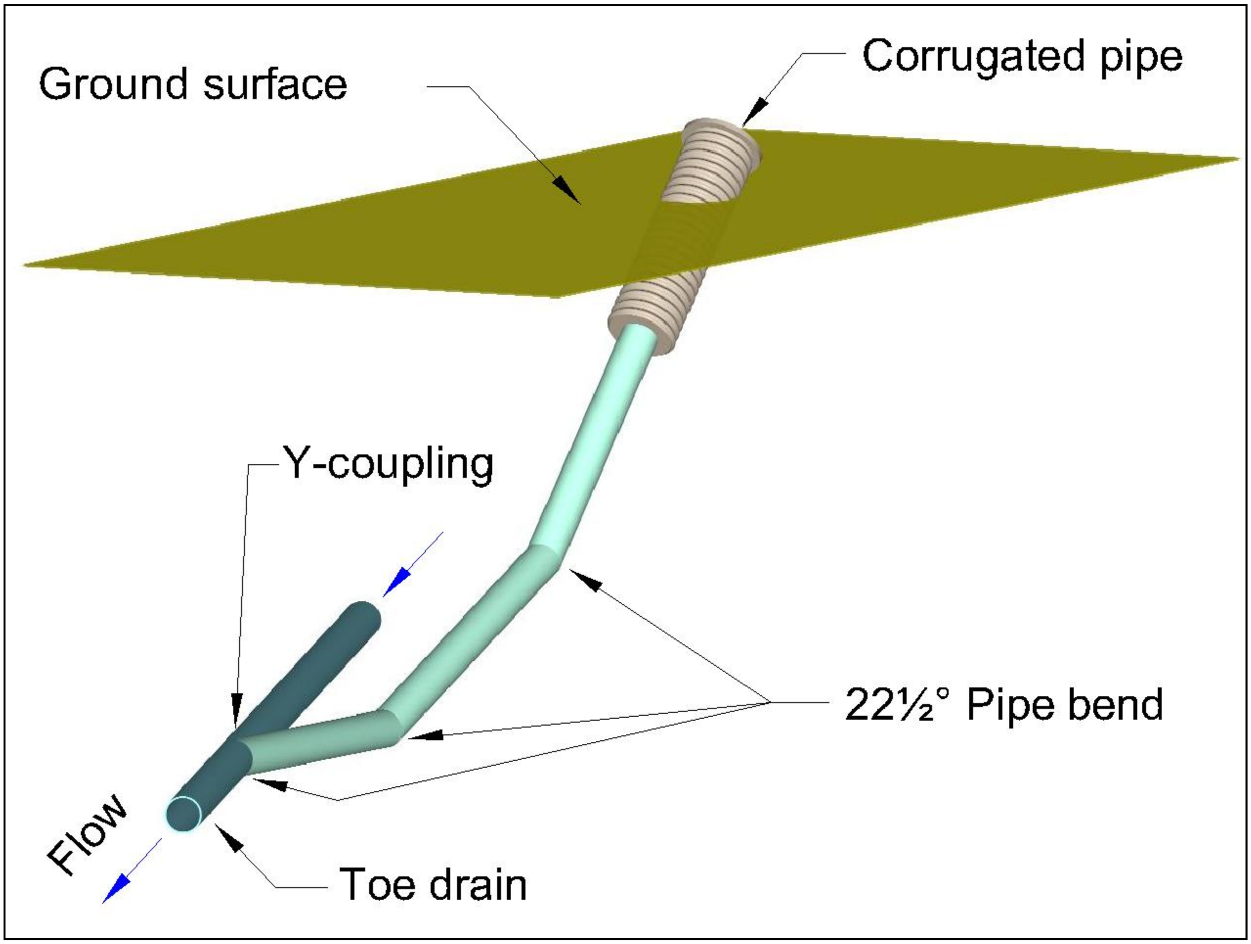

Figure E-7. Isometric view of a typical lateral access.