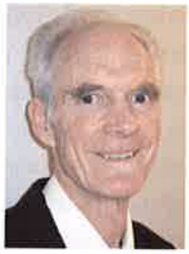
Filters for Earth Dams

Gradation Design and Construction Guidance Used by Federal Agencies



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Introduction

Between 1980 and 1985, the Soil Conservation Service (SCS), now known as the Natural Resources Conservation Service (NRCS), performed an extensive study to determine appropriate gradation criteria for sand filters to be used for filter/drainage zones in embankment dams. The study was performed at the NRCS Soil Mechanics Laboratory in Lincoln, Nebraska with the assistance of the late James L. Sherard, eminent earth dam consultant. The study included a large number of tests simulating cracks or other anomalies in dams with the potential for developing concentrated leaks under high water pressure. Filters with varying gradations were placed downstream of a simulated core material containing simulated cracks to determine the gradation necessary to prevent movement of base materials through the filter and to provide a self-healing condition. Self-healing is defined as the ability to seal cracks and stop the development of concentrated leaks and internal erosion. A large variety of materials were used to simulate the base soil of the dam upstream of the filter/drainage zone. Specific testing was performed to verify the properties of the filter that determine its ability to prevent the base or protected soil from passing through it for use in designing filter gradations. These properties included the ratio of particle size at 15 percent passing of the filter to the particle size at 85 percent passing of the base soil, uniformity of the filter gradation, and other factors influencing segregation, permeability, and grading of the filter.

The NRCS filter study was included in several papers published in ASCE publications in the 1980's [2] [3] [4]. The NRCS published guidance for filter gradation design based on the study in 1986 [7]. Several revisions have been made to the NRCS guides as the agency gained experience using the new criteria. The latest NRCS guidance, issued in October 1994, is found in Part 633 *National Engineering Handbook,* Chapter 26 *Gradation Design of Sand and Gravel Filters* [6].

Since the NRCS study, the US Army Corps of Engineers (USACE) and the Bureau of Reclamation (Reclamation) have revised their guidance for filter design. Their guidance generally conforms to the findings of the NRCS study. With further experience, both the USACE and Reclamation have modified their guidance and added important useful information about placement and construction techniques. The most recent revisions of both the USACE [9] and Reclamation [8] filter design guidance are in final draft form and are expected to be available soon. These agencies have given the authors permission to use information from their yet-to-be published revised guidance in this article.

This article is written to give the general guidance for filter gradation design and to point out some of the unique features presented by the various agencies involved. Some guidance for construction (placement, compaction, and water content) presented in the Reclamation [8] and USACE [9] unpublished guide documents is also included with the understanding that some final changes may be made before their final publication.

For this article, the particle diameter of the filter at "n" percent passing will be noted by a capital D as "D_n", expressed in millimeters. The particle diameter of the base soil or the soil protected by the filter will be noted by a lower-case d as "d_n", also in millimeters.

General Background and NRCS Study Results

Early practice for filter design used D_{15} (filter) $\leq 5 \times d_{85}$ (base soil) for sandy soils. Also, since the permeability of the filter needs to be greater than the permeability of the base soil, filters were designed with $D_{15} \geq 5 \times d_{15}$ to assure adequate drainage. Early practice for filter design generally did not address silt and clay soils.

Research by Sherard, Dunnigan, and Talbot [3] indicated that the effective pore diameter of a filter (the minimum diameter of pores that will allow soil particles to pass) is about 0.11 times the D_{15}. If the d_{85} of the soil is the same size as the effective pore diameter of the filter ($d_{85} = 0.11 \times D_{15}$), then the filter $D_{15} = 9 \times d_{85}$ of the soil. According to this finding, the early practice of using $D_{15} \leq 5 \times d_{85}$ for sandy soils provided a filter with a factor of safety of nearly 2. Current criteria use of $D_{15} \leq 4 \times d_{85}$ for sandy soils provides a factor of safety of a little over 2. The NRCS study showed that for silt and clay soils, progressive clogging occurs where the first colloidal particles pass through the filter and fine sand and silt size particles are caught. Subsequent colloidal particles are then caught forming a "filter cake" with a very low permeability. The filter cake basically seals the filter face over the width of the crack and for some distance on each side of the crack, stopping any flow through the crack. The crack then fills with soft soil from slaking of the soil on the sides of the crack. The remainder of the filter (between cracks or openings) is open for receiving seepage water through the pores of the soil. Because progressive clogging occurs with silt and clay soils, the D_{15} is allowed to be up to $9 \times d_{85}$, as explained later.

Function of Filters and Filter/Drainage Zones in Embankment Dams

A granular filter is a porous material with openings small enough to prevent migration of the protected or base soil through the filter, while sufficiently pervious to offer little resistance to seepage flow. Filters are generally placed immediately downstream of the core zone within embankment dams and in/or on foundation and abutment soils to intercept seepage flow paths or cracks and other anomalies. Seepage flow is collected in the filter, or in an additional coarser drainage zone downstream of the filter, and carried to a safe outlet while the soil upstream of the filter zone is protected against movement from erosion or high seepage gradients. The first water flow through cracks or openings in the core zone is also collected by the filter/drainage system and eroded soil particles from the sides of the crack are caught at the filter face creating a seal to stop flow in the crack or other opening as described above. When a coarser zone is used downstream of the filter, the gradation of the material in the coarser zone must be designed as a filter for the finer material in the first (filter) zone.

A filter zone in an earth dam functions in two ways. Filters support the discharge face of a soil zone where water is percolating through the pores of the soil so that the soil particles do not move (migrate into the filter

/drainage zones). Filters also intercept cracks or other defects and prevent development of a concentrated leak from the continued erosion in the crack or defect.

Tests by Perry [1] show filters that meet current gradation criteria and are in direct contact with the soil provide support to the discharge face where water is percolating out of the pores of the soil. Support is provided because soil grain contact points (filter to base soil) are close enough together that bridging occurs between the contact points and no soil particles move. It is important that filters function for all seepage gradients expected over the life of the structure.

Filters provide protection against the possible failure modes related to piping and internal erosion in embankment dams. Common failure modes that are prevented by properly installed and designed filters are as follows (sketches are courtesy of Danny McCook):

- Piping caused by seepage through zones of poor compaction or layers of high permeability where the seepage gradients are high enough to begin removing soil particles at the discharge end of the seepage path. These layers or zones can occur anywhere in the embankment from improper selection of borrow material or inadequate compaction during the placement process, but are particularly prevalent around outlet works conduits or along structures and other penetrations through the dam(see Fig. 1)

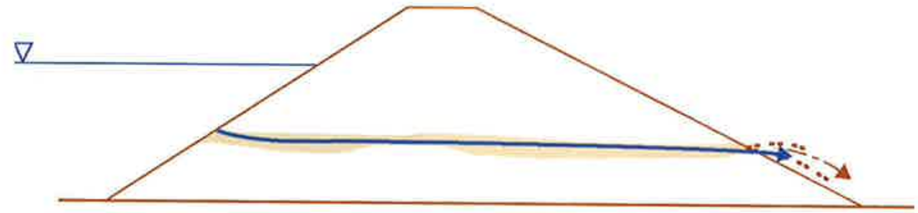

FIGURE 1 – Piping Through Embankment

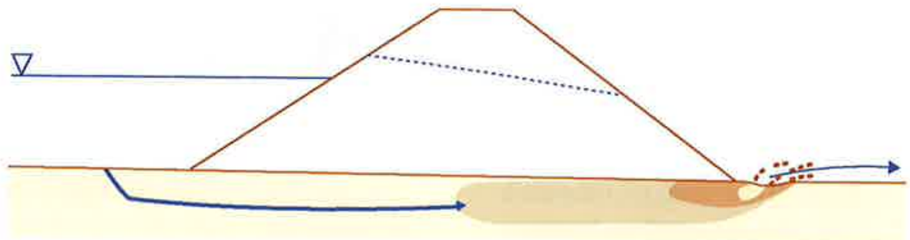

FIGURE 2 – Piping Through Foundation or Abutments

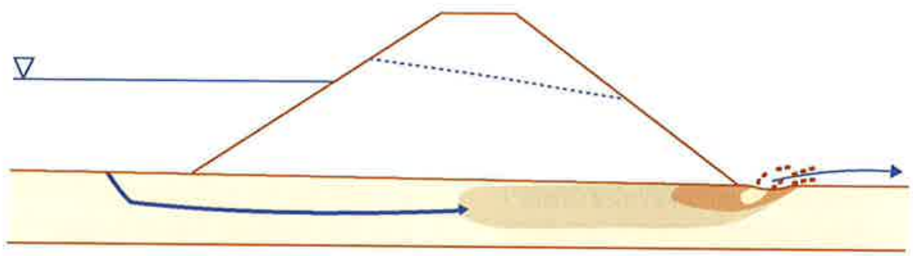

FIGURE 3 – Piping of Impervious Zone into Shell Zone

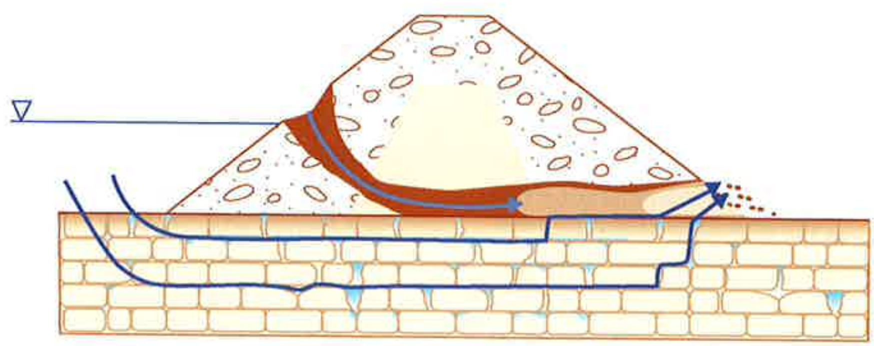

FIGURE 4 – Piping of Embankment Soil into Foundation Zones or Cracks

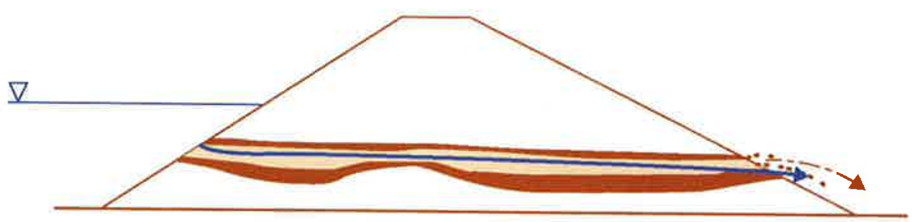

FIGURE 5 – Internal Erosion in Crack or Opening

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Filters for Earth Dams

- Piping caused by seepage through natural existing zones or layers of high permeability materials in the foundation or abutments where the seepage gradients are high enough to begin removing soil particles at the discharge end of the seepage path (see Fig. 2).

- Piping of impervious (core) zone materials into coarse shell zone materials from excessive seepage gradients at the downstream side of the impervious zone (see Fig. 3).

- Piping of embankment soil into coarse foundation materials or cracks in foundation rock where the embankment soil is in contact with these foundation layers in a downstream direction such as at the downstream side of the cutoff trench. The embankment soil is carried into and through the coarse zone creating an erosion tunnel that progresses toward the reservoir at a faster and faster rate as the gradient is increased causing a tunnel through the dam (sees Fig. 4).

- Internal erosion in cracks or other openings such as voids or anomalies in the embankment soil that is sufficient to create a concentrated leak that gets larger and larger as erosion progresses, finally causing rapid release of the reservoir through an open breach or tunnel through the dam (see Fig. 5).

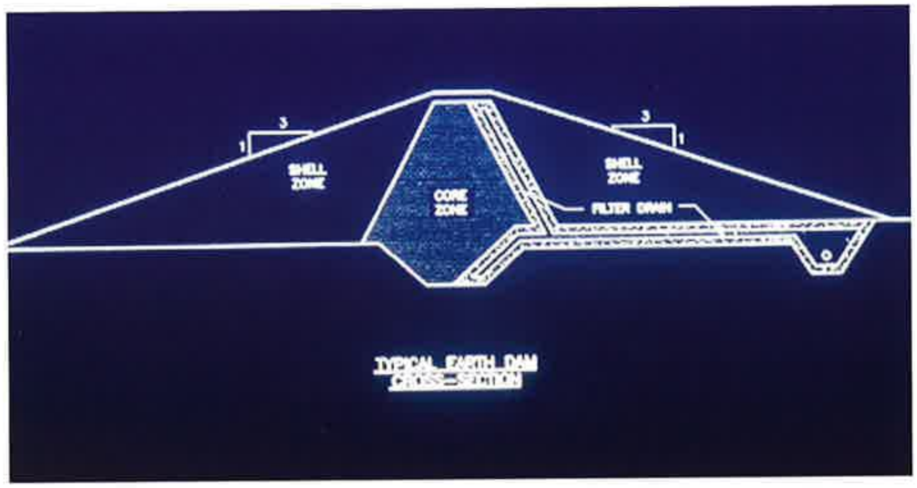

FIGURE 6 – Filter/Drainage Zones to Intercept Potential Seepage Paths

- Other failure modes associated with conditions similar to these listed.

Of the failure modes listed, internal erosion in cracks or other defects that cause openings in or through the dam is one of the most common and difficult to prevent without proper filter design and placement. Failure from internal erosion in cracks is usually rapid and complete, often on the first filling, without opportunity to intercede during the process. Generally, all earth dams are subject to cracking even when very careful construction practices are followed. Cracks can form due to stress concentrations, stress release, or differential settlement associated with abrupt changes in foundation geometry, overly steep or irregularly shaped abutments, or weak and compressible foundations. Hydraulic fracturing can occur on the first filling of the reservoir where stress release leaves the soil pressure less than the seepage pressure on the wetting front. Stress release that causes cracking is common around conduits or other structures that cause differential settlement. Defects such as openings are also more likely to exist where embankment placement and compaction are difficult or restricted, such as around outlet works conduits and along irregular foundation abutment slopes. Cracking of embankments may also be associated with seismic activity in the vicinity of the dam.

Filters provide protection for embankment dams and other earth impoundment structures that are vulnerable to the failure modes described. The filter/drainage zone should be located within the embankment or the foundation such that the seepage flow in high permeability zones or in cracks or other openings will encounter the filter/drainage zone (see Fig. 6).

Designers should obtain copies of the guides for filter design in order to understand the details of filter design. It is also advantageous to review the original work by Sherard, Dunnigan, and Talbot contained in the original ASCE Journal papers on the subject, "Basic Properties of Sand and Gravel Filters" [3] and "Filters for Silts and

Clays"[4], and by Sherard and Dunnigan, "Critical Filters for Impervious Soils" [5].

Filter Gradation Design

The three Federal agencies use a step-by-step approach for guiding the user in designing a filter gradation or to define the gradation limits to be used in the specifications for the filter. There are some minor differences in the steps used by the different agencies, but they all generally follow the same criteria. The reader should obtain a copy of one or more of the guides in order to follow all the detailed steps for designing a filter. All the details are not covered in this paper due to space limitations.

Both Reclamation and the USACE guidance warn about the appearance of a "cookbook" solution in following the step-by step method. Filter design requires considerable engineering judgment and should not be reduced to a simple "cookbook" approach. It is important for the designer to understand the engineering principals of each "Step" and the consequences of not meeting the particular criteria. The criteria were determined based on a large number of tests and by staying on the safe side of even the most critical soils including some highly dispersive clays. The boundary between success and failure for many combinations of filter and silt or clay base soil in the original testing program were above the criteria limits indicating that coarser filters may be allowed for many of these soils when specific testing verifies the desired performance. Deviation is acceptable based on sound engineering judgment, project specific analyses, and project specific laboratory testing programs.

Filter design starts with determining the grain-size distribution of the base soil to be used in the zone upstream of the filter. This soil can be an embankment zone, foundation soils, or abutment soils. It could also include an upstream filter zone in a multiple-zone design. The guidance suggests plotting the range of gradations for samples that are representative of the given zone on the typical semi-log chart used to depict the grain-size distribution of soils. Examining the range of gradation of the base soils provides for decisions to be made regarding the most critical soil gradation for designing the filter. The filter gradation should typically be designed based on the base soil with the finest d_{85} size, because that soil will require the smallest D_{15} size for the filter designed. The coarsest soil will usually control the filter permeability requirements. Outlier gradations must be carefully evaluated, and if necessary, a special filter designed and constructed where these soils can be isolated.

The NRCS study revealed that filters should be designed based on the portion of the soil that passes the No. 4 sieve. For many soils containing significant amounts of gravel size particles, the filter will be too coarse if it is designed on the basis of the total soil gradation. If the grain-size distribution curve for the base soil chosen for designing the filter has material larger than the No. 4 sieve, an adjusted curve must be plotted where the plus No. 4 material is removed (mathematically) in order to obtain the parameters for designing the filter. A corrected gradation curve is determined by dividing 100 by the percent passing the No. 4 (4.75 mm) sieve to obtain a correction factor and then multiplying the percentage passing each sieve size of the base soil smaller than No. 4 (4.75 mm) by the correction factor. The new or adjusted percentages are plotted to provide a grain-size distribution curve that is used to determine the maximum D15 of the filter. This correction will also provide a filter suitable for protecting soils that are internally unstable (the fine portion can be carried through the coarse portion with flowing water).

The USACE and Reclamation guidance [8] [9] have one additional step for evaluating the base or protected material regarding whether it is gap-graded. Reclamation procedures do not require calculating a regraded curve for designing a filter for base soils that meet these requirements:

1. The base soil is in category 4 (see Table 1) – has less than 15 percent fines, and
2. The soil is not gap-graded
3. The base soil is not broadly graded, using the definitions of

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TABLE 1 - CATEGORIES OF BASE SOIL MATERIALS

Base Soil Category	Percent Finer Than The No. 200 Sieve (0.075mm)(after regrading where applicable)	Base Soil Description
1	> 85	Fine silts and clays
2	40 – 85	Sands, silts, clays, and silty and clayey sands
3	15 – 39	Silty and clayey sands and gravel
4	< 15	Sands and gravels

these terms in the Unified Soil Classification System (the Coefficient of Uniformity is less then 4 for gravels and less then 6 for sands, and the Coefficient of Curvature is between 1 and 3)

Reclamation provides a definition of gap-graded soils [8] which is the same as the Unified Soil Classification System definition for broadly graded or well graded soils.

Next, the base soil is classified into one of four categories for determining the maximum D_{15} size of the filter based on the percentage of the base soil that passes the No. 200 sieve (percent fines) for the adjusted curve after correcting for the material larger than the No. 4 (4.75 mm) sieve (regrading). The categories are given in Table 1.

The criteria for determining the maximum D_{15} size of the filter for each category of base soil are shown in Table 2.

TABLE 2 - FILTERING CRITERIA, MAXIMUM D_{15}

Base Soil Category	Filtering Criteria, D_{15} max [(a)]
1	$\leq 9 \times d_{85}$ but not less than 0.2mm [(c)(d)]
2	$\leq 0.7mm$
3	$\leq \frac{(40-A)}{(40-15)}\left[\left(4 \times d_{85}\right) - 0.7mm\right] + 0.7mm$ A = percent passing the No.200 (0.075 mm) sieve after regrading. If $4 \times d_{85}$ is less than 0.7 mm, use 0.7 mm.
4	$\leq 4 \times d_{85}$ of base soil after regrading [(b)]

The following notes apply to the UASCE guidance for Table 2:

a) The maximum D_{15} may be adjusted for certain non-critical uses of filters where significant hydraulic gradients are not predicted, such as bedding beneath riprap.

b) The maximum $D_{15} \leq 4 \times d_{85}$ criterion should be used in the case of filters beneath riprap subject to wave action and in the case of drains and well packs, which may be subject to violent surging and/or vibration.

c) For fine clay base soil with d_{85} between 0.03 and 0.1 mm, a maximum D_{15} up to 0.5 mm may be used.

d) For fine-grained silt with low sand content, a maximum D_{15} of 0.3 mm may be used.

The following notes apply to the Reclamation guidance for Table 2:

a) Filters are to have a maximum particle size of 2 inches (50 mm) and a maximum of 5 percent passing the No. 200 (0.074 mm) sieve, after compaction, with the plasticity index (PI) of the fines equal to zero. PI is determined on the material passing the No. 40 (0.425 mm) sieve in accordance with USBR 5360, *Earth Manual,*

TABLE 3 - PERMEABILITY, PARTICLE SIZE & PI CRITERIA

Agency	Permeability Requirements, based on the base soil before regrading		Maximum Particle Size	Max. % Fines (< # 200 sieve)	PI of fraction < # 40 sieve
NRCS	$D_{15} \geq 4 \times d_{15}$	But not less than 0.10 mm	3-inches	5	0
Reclamation	$D_{15} \geq 5 \times d_{15}$	But not less than 0.10 mm	2-inches	5*	0
USACE	$D_{15} \geq 3$ to $5 \times d_{15}$	But not less than 0.10 mm	3-inches	5	0

*Reclamation cautions that fewer fines may be considered when cracking of the filter is a concern.

TABLE 4 - SEGREGATION CRITERIA FOR ALL BASE SOIL CATEGORIES

If Minimum D_{10} is: (mm)	The Maximum D_{90} is: (mm)
< 0.5	20
0.5 – 1.0	25
1.0 – 2.0	30
2.0 – 5.0	40
5.0 – 10	50
> 10	60

Part 2. To ensure sufficient permeability, filters are to have a D_{15} size equal to or greater than $5 \times d_{15}$ but no smaller than 0.1 mm.

b) In category 4, the d_{85} may be determined from the original gradation curve of the base soil with out adjustments for particles larger than 4.75 mm, provided that the soil is not gap-graded or broadly graded. (There is a reference to paragraph 5.10 in the Reclamation guide for definitions of gap-graded and broadly graded).

Criteria are used to ensure the filter is designed with sufficient permeability that it will not restrict the flow from the adjacent embankment or foundation zone into the filter zone. All agencies use criteria for the filter D_{15} being equal to or larger than a multiplier of the d_{15} of the base soil before regrading. Additionally, there are criteria for maximum particle size, maximum percent fines (% passing the No. 200 sieve) and for the plasticity index (PI) of the fraction of the filter passing the No. 40 sieve. Some agencies have slightly different criteria for these characteristics. The criteria are shown in Table 3.

A relatively uniform gradation is desirable for the filter. The NRCS and USACE criteria include requirements for the specified upper and lower limits of the filter design band to have a coefficient of uniformity ($C_u = D_{60}/D_{10}$) less than 6. These two agencies also require that the distance between the coarse side limit and the fine side limit be no greater than a multiple of 5 for any percent passing value less than 60 percent passing. For example, if the minimum D_{60} is set at 0.5 mm, the maximum D_{60} cannot be more than 2.5 mm. This requirement is used to prevent any gap-graded or widely graded filters from being used. Reclamation guidance is that the gradation limits near the middle of the curve should not differ more than 35 points (35%).

To minimize segregation of the filter material during placement, all three agencies use the same criteria for the maximum ratio of the D_{90} / D_{10} sizes in the filter as given in Table 4.

For determining the coarse and fine side limits of a band that defines an acceptable filter that can be used in the construction specifications, the recommended procedure is as follows:

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1. Find the maximum D_{15} of the filter for preventing movement of fines and the minimum D_{15} of the filter to ensure adequate permeability using the appropriate criteria applied to the soil that will be immediately upstream of the filter. These points are plotted on a typical semi-log grain-size distribution chart and the distance between the maximum and minimum checked to see that there is not more than a multiple of 5 between them.
2. The NRCS and USACE recommend that when these initial design points are too far apart and where filtration is most important, the maximum D_{15} be moved toward the fine side to achieve the maximum multiplier of 5. For those soils where permeability is most important, the minimum D_{15} is moved toward the coarse side to achieve the maximum multiplier of 5.
3. The limits at 60 percent and 10 percent passing are then set for a uniformity coefficient (C_u) of less than 6 for each of the upper and lower limits of the gradation band. The maximum particle size (3-inches (76.2 mm) using NRCS and USACE criteria or 2- inches (50.8 mm) using Reclamation criteria and the limit of 5 percent passing the No. 200 sieve are plotted. The maximum D_{90} is plotted from the guidance in Table 3.
4. With these points plotted on the semi-log grain-size distribution chart, the coarse and fine limits for the filter band can be shown by connecting the points on the coarse and fine sides with straight lines. The limits for the filter band are usually given in a table in the specifications or on the drawings using values that are usually rounded off to the nearest 5 percentage points, but perhaps to the nearest 2 percentage points near the 15 percent passing line. An example filter gradation specification is shown in Table 5 as follows:

TABLE 5 - FILTER DESIGN SPECIFICATION LIMITS

Sieve Size	Percent Passing
(mm)	
1-Inch (25 mm)	100
1/2 -inch(12.5 mm)	90-100
No. 4	70-100
No. 10	52-85
No. 20	30-70
No. 40	10-56
No. 100	0-26
No. 200	0-5

The base soil and filter gradation limits for the filter design in Table 5 are shown in Figure 7. The filter design limits are for the maximum allowable C_u value of 6 for the fine and coarse limits of the specified filter band. The filter limits could be for a more uniform gradation such as the one shown as "Alternative Filter Design Limits" in Figure 7, which have a C_u value of about 3.5 for the fine and coarse limits of the filter band.

Use of Standard Gradations

For smaller projects and those where on-site materials are not suitable for manufacturing the filter/drain materials, these materials are obtained at off-site sources. It is often less expensive and advantageous to use standard ASTM or AASHTO gradations or some locally supplied gradation that is stockpiled at quarries or sand and gravel suppliers. State and federal highway department standards are often good sources of commercially manufactured and supplied gradations. The fine and coarse limits of the gradations specified can often be adjusted within the plotted allowable points determined during the filter design process to meet the requirements of these standard gradations. Each of the federal agencies has addressed the use of standard commercial gradations in their guidance documents. The NRCS guide [7] provides the ASTM gradations in table form and grain-size-distribution plots of most them are also provided.

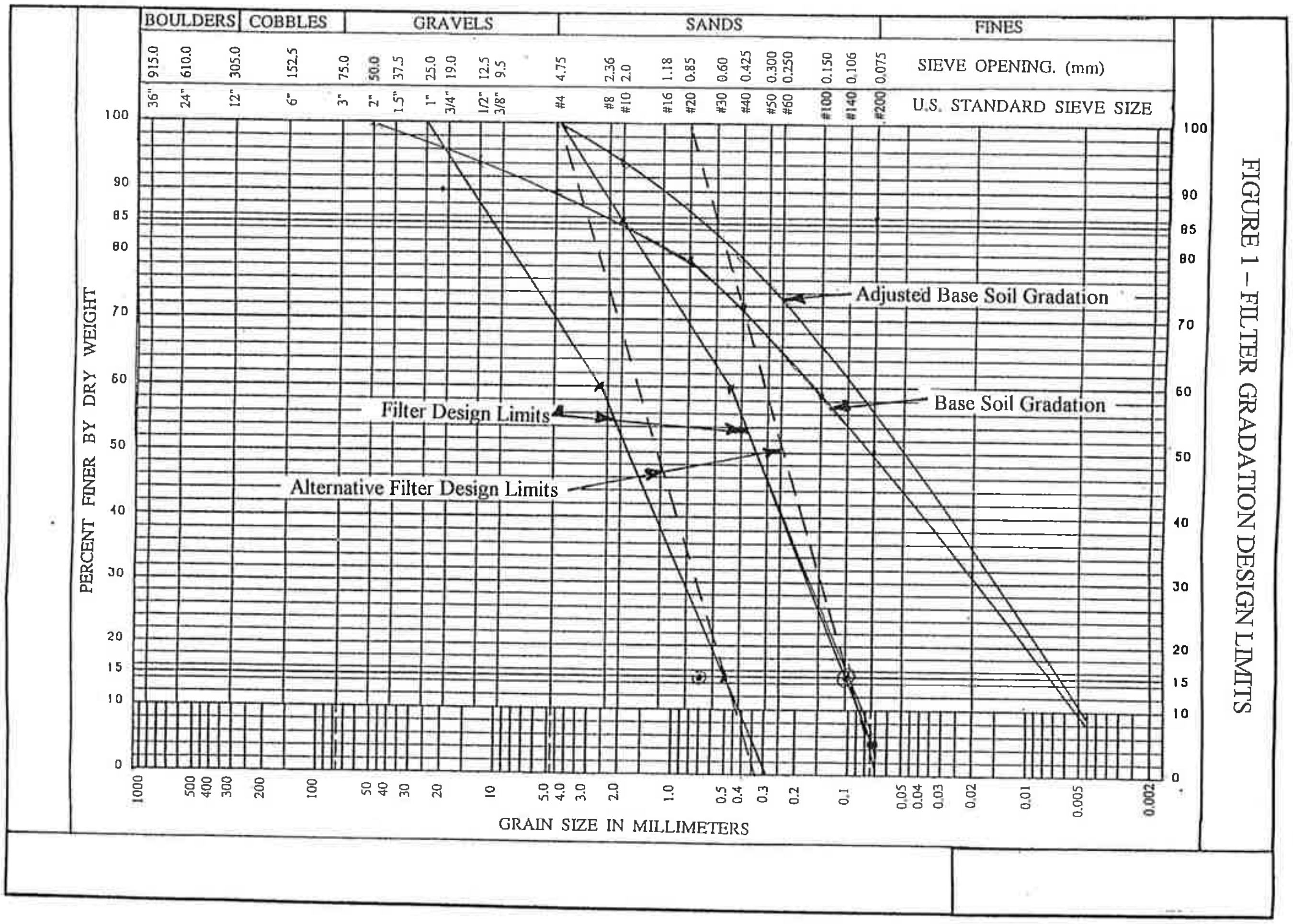

FIGURE 7 – Example of Filter Grading Design

Design of Perforated Pipe and Multi-Stage Filter Systems

Often, a filter design incorporating a perforated pipe and a relatively fine-grained base soil will require multi-stage filters. Multi-stage filter systems may also be needed when transitioning from fine to coarse materials or from coarse to fine materials in a zoned embankment, where rockfill is used for the shell zone, or where coarse material is required for improving the water-carrying capacity of the system.

In multi-stage filter design, each layer must meet filter requirements with respect to adjacent materials in an upstream direction. When designing a multi-stage filter/drainage system, design of the second filter is similar to the design of the first filter. The first filter now becomes the base or protected material. For stability against piping, the maximum D_{15} of the second (coarse) filter, and thus the coarse side of the filter band, is controlled by the minimum d_{85} on the fine side of the first (fine) filter gradation band. For permeability, the minimum D_{15} of the second (drain rock) filter, and thus the fine side of the filter band, is controlled by the maximum d_{15} on the coarse side of the first (sand) filter gradation band. In summary, when dealing with more than one gradation band, the fine side of the protected material gradation controls the coarse side of the filter and the coarse side of the protected material gradation controls the fine side of the filter.

If a collector pipe is embedded in the final drain zone or coarse stage, the gradation of this zone must also meet gradation/particle size requirements with respect to the diameter or width of the pipe openings. Each agency has somewhat different criteria for the perforation size or slot width in relation to the gradation of the material in the drainage zone or filters surrounding the drain pipe as shown in Table 6.

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TABLE 6 – PERFORATION OR SLOT SIZE FOR DRAIN PIPE

Agency	Perforation Size or Slot Width	
NRCS	$\leq D_{85}$ Filter – non critical drains – no surging	$\leq D_{15}$ Filter – critical drains w/surging or gradient reversal
Reclamation	$\leq D_{85}$ Filter $\div$ 2 for uniformly graded materials	$\leq D_{85}$ Filter $\div$ 4 for broadly graded materials – only slotted pipe (no perforations)
USACE	$\leq D_{50}$ Fine limit of the filter band	

Construction and Other Guidance

Reclamation provides guidance on broadly graded, gap-graded, and internally unstable soils. A section on heterogeneous base soils such as glacial deposits and the judgments that must be made concerning how to design for a layered system of fine and coarse base soils where a filter for the fine portion will have a permeability too low for the coarse layers is included. These recommendations are not included in this article. Those who may have these conditions should obtain a copy of Reclamation guidance [8] for reference.

Reclamation also has guidance on sizing of filter zones. The width or thickness should be large enough to carry the estimated seepage quantity with a large safety factor. Constructability is also a factor in blanket and chimney drains. A minimum thickness of blanket drain is recommended to be 18 inches (.45 m) for ideal conditions and a desired thickness of 36 inches (0.90m) with a strong suggestion that it be much thicker on slopes and other difficult terrain. A minimum width of 8 to 10 feet (2.4 to 3.0 m) is recommended for chimney drains and vertical or inclined filters in embankments, but 16 feet horizontal thickness is preferred by contractors when bottom dump hauling equipment is used to place the filter zone. Chimney drains as narrow as 3-feet in width have been successfully used when the "trench back method" is used. See the Reclamation guidance [8] for a detailed description of this method.

FIGURE 8 – Filter/Drainage Zones are Maintained Higher than Adjacent Zones

Both the USACE and Reclamation have guidance on construction. Generally they suggest the durability of materials used in filter/drainage zones meet the durability requirements of concrete aggregate. Close inspection is important during construction. Contamination is to be avoided by keeping the filter/drainage zone higher than the adjacent zones during placement and compaction and by avoiding equipment crossings (See Figure 8). Removal of contaminated material is necessary when it occurs.

Methods for preventing segregation are a critical component of filter/drain construction. Generally the free-fall associated with dumping or other placement methods should be limited to two feet (0.6 m). Lift thickness should be closely controlled. Spreader boxes or bin-type boxes that control the lateral limits and lift thickness are recommended (see Figure 9).

FIGURE 9 – Box for Placing Filter/Drain Material in Chimney Drain

Horizontal and vertical alignment is very important, especially for vertical or sloping chimney drains. When the horizontal location is missed by only a short distance on a given lift, the effective width of the filter zone may be substantially reduced.

Filters should be compacted, but they should not be compacted excessively. Excessive compaction can breakdown the particles, reducing the permeability of the filter and increasing the fines content. These two agencies both recommend compaction of the filter so the minimum in-place density will not be less 70 percent of relative density. This will usually require water be added immediately prior to compaction to bring the water content up to near saturation. The authors have observed placement techniques where a water truck sprayed water on the lift of filter immediately in front of the vibrating roller to achieve near saturation conditions for compaction.

The USACE filter design guide includes a section on the layout of filters and drains to facilitate monitoring and the evaluation of drain performance. Specifically, the layout and design of the drainage system should be such that manholes with measuring weirs and sediment traps are located where these items can be used to monitor seepage flow from critical areas of the dam. They are also located to provide access for inspection cameras and clean-out equipment. Monitoring during initial filling is very critical and also after events such as earthquakes, and rapid filling or lowering of the reservoir. The USACE also recommends monitoring turbidity of the drain discharge.

Summary

Current practice for filter design was developed based on an extensive study conducted between 1980 and 1985 by the NRCS. Three major agencies (USACE, Reclamation, and NRCS) involved in earth dam design have developed guidance for filter design based on the NRCS study. The study verified the parameters of the filter that determine its ability to prevent passage of the upstream base soil (usually the core zone of the dam or foundation and abutment soil) through the filter. The study also determined the criteria for designing the proper gradation of the filter to catch soil particles arriving at the filter face. The criteria are basically the same for each agency with some minor differences.

Properly designed filters are critical for protecting earth dams against failure from:

1) piping caused by excessive seepage gradients through poorly compacted or pervious layers or zones in embankments or foundations;
2) piping of impervious zone materials into coarse shell zone materials;
3) piping of embankment material into coarse foundation layers or cracks such as at the downstream face of the cutoff trench;
4) internal erosion and the development of concentrated leaks through cracks and other anomalies.

Cracking is a common defect found in earth dams because of stress concentrations from differential settlement and construction problems associated with structures such as the outlet works. Filters support the discharge face where water is percolating through the soil pores and they catch soil particles where water is passing through cracks or other openings, creating a filter cake at the face of the filter. The filter cake has a very low permeability over the width of the crack and for some distance on each side of the crack. The remainder of the filter is open to receive seepage through the soil pores.

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Using the step-by-step procedures in the various guides, an adequate filter can be designed for any soil. Using these design guidelines, filter gradations will be relatively uniform, gap-grading or skip-grading will be prevented, and the filter will have sufficient permeability to allow free flow of seepage water from the upstream soil zone. Segregation will also be minimized. The results of the procedure provide fine and coarse limits of a filter band that can be used to provide specifications for the filter gradation that allow some latitude in the production of the filter material. Guidance is also provided on the proper relationship between filter gradation and drainpipe perforation size.

The USACE and Reclamation guides include recommendations for construction, including durability of materials, placement and compaction, and inspection requirements.

While this article has given the basic filter gradation design procedures, it is recommended the reader obtain one or more of the referenced guides so that all of the details of the procedure can be followed.

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