Thoughts on Soil Filter Gradation Design

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Introduction

Three papers published in the 1980s (Sherard et al, 1984a, 1984b; and Sherard & Dunnigan, 1989) presented the results of Natural Resources Conservation Service (NRCS)[1] research on soil filters. Between the mid-1980s and the mid-1990s, the NRCS; the US Department of the Interior, Bureau of Reclamation (Reclamation); and the US Army Corp of Engineers (USACE) incorporated the results of that research into published guidelines on soil filter gradation design. These guidelines, and their subsequent updates, now represent the state of the practice for soil filter gradation design.

The research and the resulting guidelines were a substantial advancement in soil filter design. All of the noted agency guidelines and a subsequently published Federal Emergency Management Agency (FEMA) document (FEMA, 2011) present step-by-step procedures for establishing limits for soil filter gradations. Some agencies, organizations, and practitioners have incorporated the step-by-step guidance into spreadsheet applications to facilitate calculations. One clear advantage to the step-by-step guidelines is consistency in filter gradation design calculations among different practitioners. However, a potential pitfall is that practitioners using the step-by-step procedure may not understand the specific purposes of the various steps and the

[1] In this article, NRCS is used to stand for the Natural Resources Conservation Service and its predecessor agency the Soil Conservation Service (SCS). The agency was the SCS at the time of the referenced research.

latitude that is available in applying them. This can lead to the specification of filter gradations that are overly expensive and difficult to produce.

The NRCS guidance (NRCS, 1994/2017) actually states:

> Even though the step-by-step guidance may appear to be promoting a "cookbook" solution, filter design requires considerable engineering judgment and should not be reduced to a simple cookbook approach. The designer must understand what each step entails and the consequences of not meeting the particular criteria.

This article presents a brief history of soil filter gradation design and then uses two examples of application of the step-by-step process to illustrate latitude available to designers.

History of Soil Filter Gradation Design

In the early 1920s, Karl Terzaghi developed the concept of a weighted filter to prevent heave at the downstream toe of a dam founded on cohesionless soil (Terzaghi, 1922). In the early 1930s, while working on the Bou-Hanifa Dam in Algeria, Terzaghi completed laboratory testing and developed empirical filter criteria that included particle retention and permeability requirements, but he did not publish the criteria at that time (Fannin, 2008). In 1939, he published his filter criteria (Fannin, 2008; Terzaghi, 1939): $D_{15F} < 4 \times D_{85B}$ for particle retention and $D_{15F} > 4 \times D_{15B}$ for permeability, where D_{15F} is the particle size in the filter for which 15% of the particles are finer (by dry weight), D_{85B} is the particle size in the base soil (the soil to be filtered) for which 85% of the particles are finer, and D_{15B} is the particle size in the base soil for which 15% of the particles are finer.[2] In 1940, G. E. Bertram confirmed that Terzaghi's filter criteria were adequate, with a factor of safety of about 2, through rigorous laboratory testing at Harvard University (Bertram, 1940).

In the 1950s, Reclamation completed laboratory filter investigations and suggested that filter criteria should be based upon D_{50F} rather than D_{15F} (Karpoff, 1955). This was later found to be incorrect, although references to it exist in some historic publications. Interestingly, Reclamation also recognized that large particles skew filter design and regrading should be conducted for filter design, although to the writer's knowledge this suggestion was not widely incorporated into practice until after the SCS/NRCS work was published in the 1980s.

In the 1980s, the previously referenced SCS/NRCS research confirmed that Terzaghi's original filter criteria were appropriate for clean, coarse-grained soils (sands and gravels with less than 15% finer than the #200 sieve), but different criteria were needed for finer grained soils, especially silts and clays. The results also demonstrated the importance of mathematically regrading base soils before filter design so that the resulting filter adequately protects the finer portion of the base soil gradation.

In the late 1990s and early 2000s, Mark Foster and Robin Fell from the University of New South Wales, Australia reviewed the 1980s NRCS work in detail and conducted some additional filter testing. They generally corroborated the earlier results but recommended slightly finer filters for dispersive soils (Foster & Fell, 2001), recommendations that were subsequently included in the published guidelines.

The practical implication of this history of filter criteria development is that anything designated as a filter in design or construction documents prepared before the 1980s and 1990s was not developed according to the current state of the practice criteria. The earlier filters were likely developed according to Terzaghi's criteria, and the filter designs likely did not include regrading of the base soils. Hence, engineers assessing dam designs from before the 1980s to 1990s should be cautious in their assessments of the effectiveness of materials designated as filters. Based on the writer's experience, in some cases, ASTM C33 fine aggregate or similar gradations were used for filters, which most likely would serve as good filters, but in other cases filters selected to conform to the Terzaghi criteria may be too coarse to function properly.

Because the modern filter gradation design criteria include some factor of safety, some materials that do not meet modern criteria may still provide adequate filter performance. Foster and Fell (2001) provided guidance on how to assess the potential filter performance of materials not designed to modern criteria, but it is important to note that this guidance is intended for evaluation of existing dams and risk imposed by materials not meeting modern criteria, not for design of new dams or dam modifications.

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[2] The symbology used in the report differs from that originally used by Terzaghi, but the meanings of the equations are the same.

Filter Design Examples

The following filter design examples and discussions are based on the most recent NRCS guidelines (NRCS, 1994/2017). The procedures in the other guidance documents from the federal agencies (FEMA, 2011; Reclamation, 2011; USACE, 1993, 2004) are essentially the same, with generally minor variations among the different documents.

The NRCS procedure results in the calculation of seven control points to provide guidance for filter gradation specifications, as illustrated in Figure 1. Interpolation and extrapolation are then used to construct lines that define an acceptable range for a filter, also as illustrated in the figure. This range can in turn be used to define filter gradation specifications.

It is important to understand the reasons for each of these control points. Point 1, referred to as D_{15Fmax}, is the maximum D_{15} size to satisfy particle retention requirements—that is to provide an effective filter. Point 2, D_{15Fmin}, is the minimum D_{15} size to provide permeability significantly greater than that of the base soil. Points 3 and 4, D_{60Fmax} and D_{60Fmin}, are maximum and minimum D_{60} sizes to assure a uniform filter gradation, specifically a coefficient of uniformity, C_u[3], no greater than 6. The reason for a uniform gradation is to prevent the filter from being susceptible to internal instability, which can occur in gap graded soils or in broadly graded soils with flat sections of the gradation curve. Points 5 and 7, $D_{100Fmax}$ and D_{90max}, are intended to reduce the likelihood of particle segregation during handling and placement by limiting the amount of coarse particles. Finally, Point 6, requiring that the percent passing the #200 sieve be no greater than 5, limits the potential for fines, particularly plastic fines, which could increase the ability for the filter to hold an open crack, and also promotes permeability. Although it may not be expressly stated in the guidelines, the intention of the Point 6 requirement is for the filter to have no more than 5% finer than the #200 sieve in place, after compaction. Filter materials can sometimes experience particle breakdown during transportation and compaction, resulting in an increase in the percent finer than the #200 sieve. Specifications and quality control/quality assurance procedures should ensure that this requirement is met in place, after compaction.

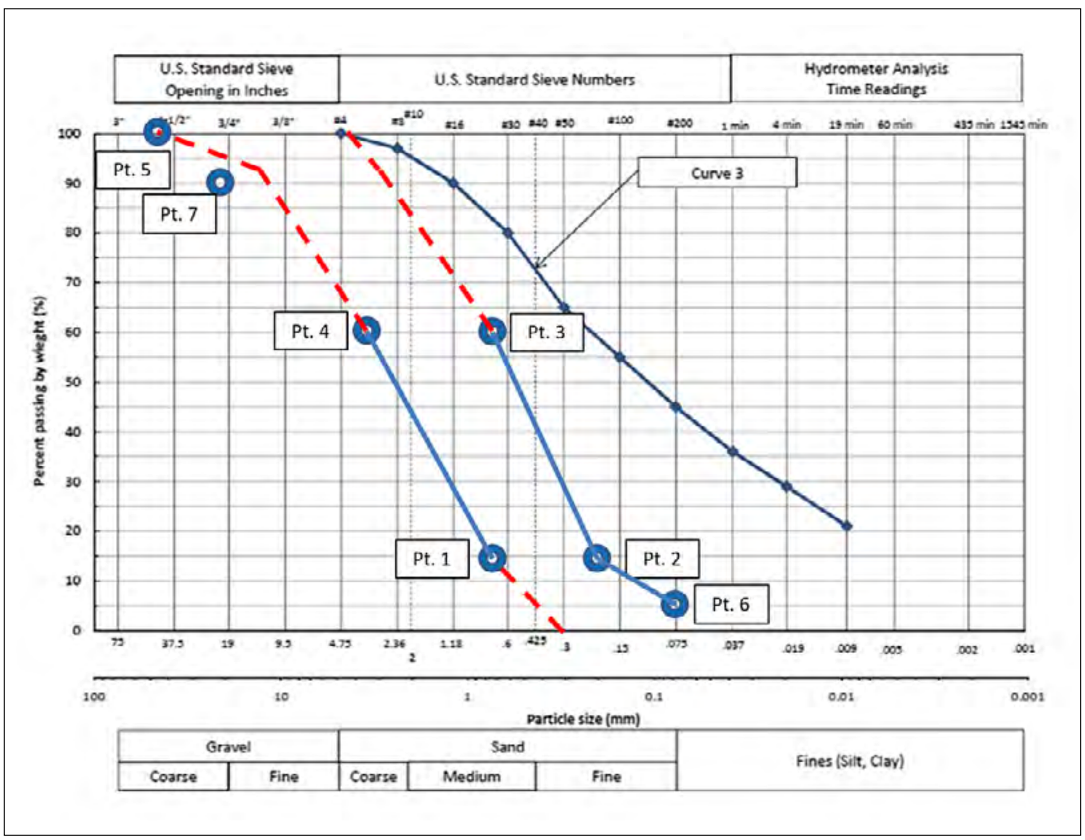

Figure 1 Control Points for Filter Gradation Design

[3] Coefficient of uniformity is defined as $C_u = D_{60}/D_{10}$.

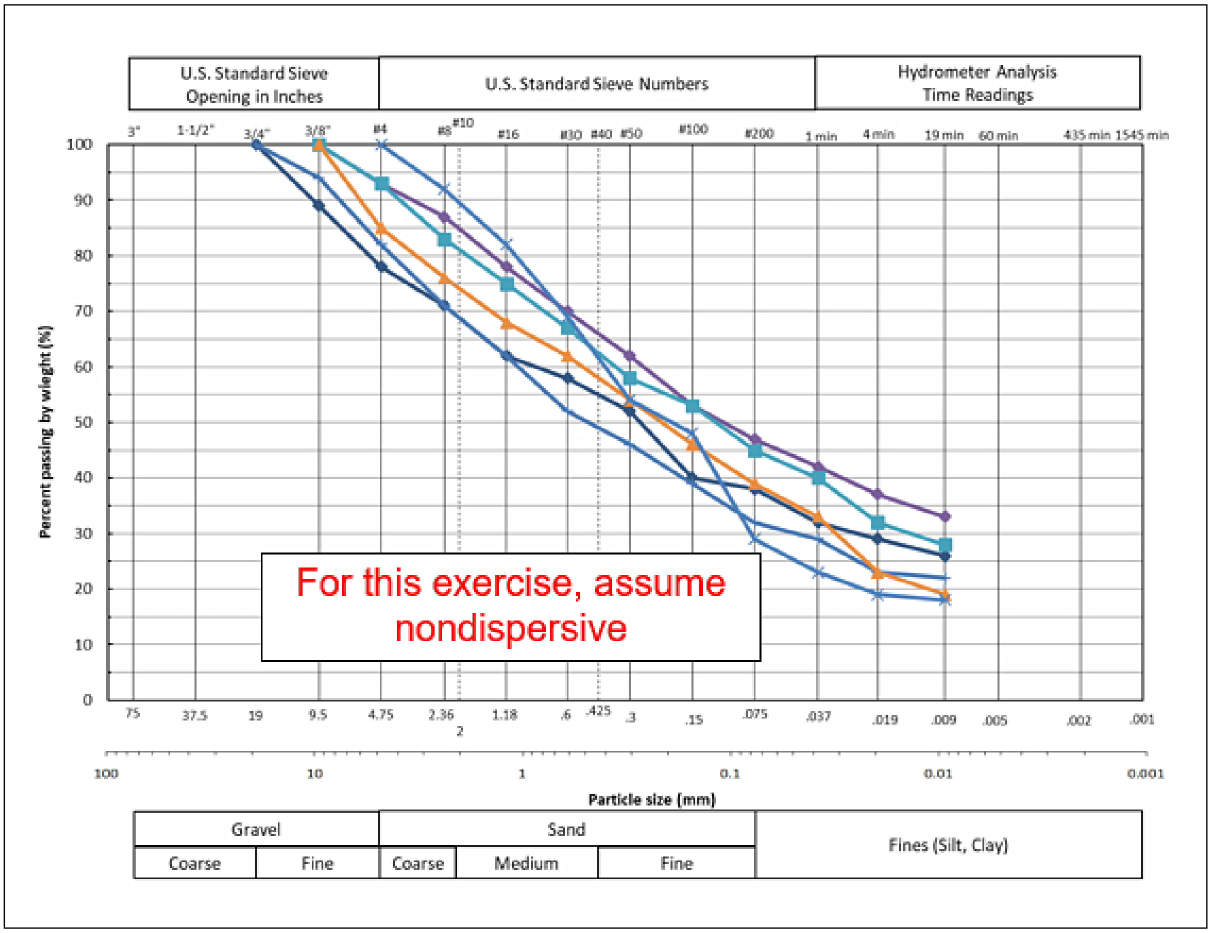

Figure 2 Base Soil Gradation Curves

The complete design process can best be illustrated through an example using the NRCS step-by-step instructions. Consider designing a filter for a base soil represented by the six gradation curves shown in Figure 2. In the writer's experience, the gradations shown in Figure 1 are not unusual for homogeneous embankments or foundation soils, and in some cases clayey or silty sands like these have been used for embankment cores.

The step-by-step filter gradation process follows.

Step 1. Evaluate whether the base soil is dispersive. In practice this would be done through testing (e.g., crumb, pinhole, or double hydrometer tests). For purposes of this example, the base soil will be assumed to be nondispersive.

Step 2. Determine if the base soil has any gravel size particles; that is particles coarser than the #4 sieve size. In this case, five of the six gradation curves indicate particles coarser than the #4 sieve.

Step 3. Mathematically regrade any soils that include gravel size particles. For all particle sizes equal to or finer than the #4 sieve, divide the percent passing for that sieve size by the uncorrected percent passing the #4 sieve converted to a decimal, as illustrated in Figure 3. The resulting regraded gradation curves are shown in Figure 4.

Sieve	Size	Percent Finer	Percent Finer
¾"	19.1	100	
½"	12.7	100	
3/8"	9.5	100	
#4	4.75	93	100
#8	2.36	87	94
#16	1.18	78	84
# 30	0.6	70	75
# 50	0.3	62	67
# 100	0.15	53	57
# 200	0.075	47	51

Divide by 0.93

Figure 3 Mathematical Regrading Example

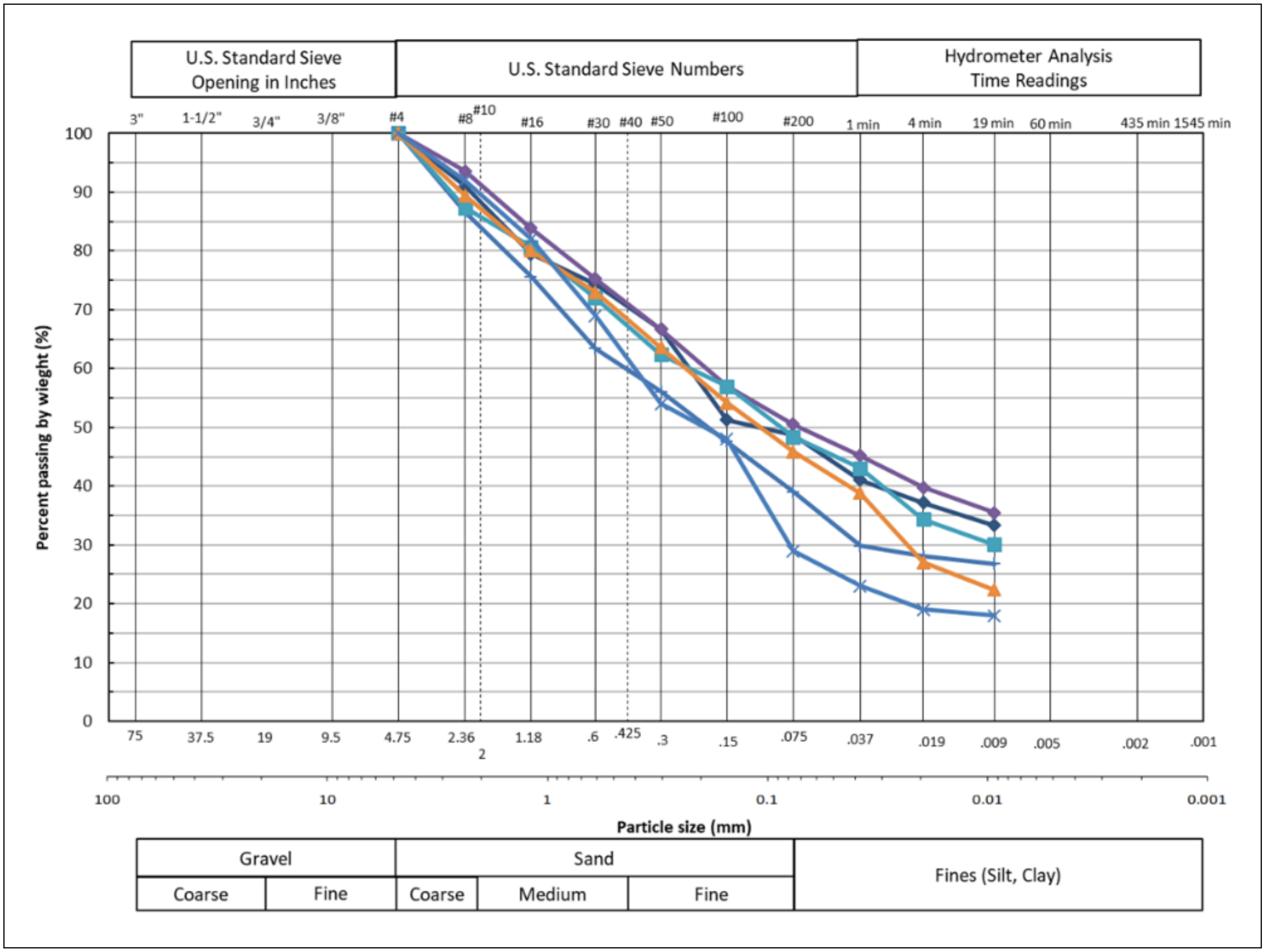

Figure 4 Regraded Base Soil Gradation Curves

Percent Finer than # 200 Sieve	Category of Base Soil
> 85	1
40-85	2
15-39	3
< 15	4

(a) Category table

Base Soil Category	Percent Finer Than No. 200 sieve (A)	Base Soil Description	Filter Criteria
1	>85	Fines silt and clays	D_{15F} = 9 x D_{85B}, but not < 0.2mm, unless dispersive, then D_{15F} = 6.5 x D_{85B}, but not < 0.2mm
2	40 - 85	Sands, silts, clays, and silty and clayey sands	D_{15F} = 0.7mm, unless dispersive, then D_{15F} = 0.5mm
3	15 - 39	Silty and clayey sands and gravels	$D_{15F} = 0.7mm^* + \frac{(40 - A)(4 \times D_{85B} - 0.7mm^*)}{25}$ A = % passing No. 200 sieve When A < 4 x D_{85B}, use 0.7 mm* *If dispersive, use 0.5mm instead of 0.7mm
4	<15	Sands and gravels	D_{15F} = 4 x D_{85B}

(b) Filter criteria table

Figure 5 Tables for Selection of Base Soil Category and Filter Criterion (From NRCS, 1994/2017)

Note that mathematical regrading of the base soil is not required if the following three criteria are all met:

1. The base soil contains less than 15% fines.
2. The base soil is not gap graded.
3. The base soil is not broadly graded; the coefficient of uniformity, Cu, is not greater than 6 and the coefficient of curvature, Cz [4], is not between 1 and 3.

Step 4 and 5. Select the gradation with the greatest percentage passing the #200 sieve as the critical gradation for particle retention. In this case, that is the gradation curve shown in purple in Figure 4, with 51% passing the #200 sieve. The base soil category is then selected from the table shown in Figure 5a, in this case Category 2. The filter criterion is then taken from the table shown in Figure 5b, which indicates D_{15Fmax} of 0.7 mm for this nondispersive base soil.

There are some cases when it may be reasonable to select a base soil gradation different from the finest gradation. For example, if the available gradation curves are from a borrow study before construction and the soils will be mixed during borrow operations, it may be reasonable to use an average gradation curve or a curve slightly finer than average. Base soil selection is discussed in some detail in Reclamation (2011) and Pabst and France (2010).

Step 6. The next step is to determine the value of D_{15Fmin} to provide adequate permeability. According to the NRCS method, this value is initially estimated as the greater of $(D_{15Fmax})/5$ or 0.1 mm. It is further suggested that this be checked against a second criterion that D_{15Fmin} be greater than 4 to 5 times D_{15B} for the coarsest base soil before regrading.

For this example $(D_{15Fmax})/5 = 0.7$ mm$/5 = 0.14$ mm, which is greater than 0.1 mm. To complete the recommended check, consider the unregraded curves in Figure 2. It is somewhat difficult to determine which curve is the coarsest, and none of the curves extend to D_{15}. Nonetheless, it can be concluded that D_{15B} would be less than 0.009 mm. Using that value, 4 to 5 times D_{15B} is less than 0.036 mm to 0.045 mm, both of which are less than 0.14 mm, so no adjustment is needed.

In some cases, there can be challenges in meeting the requirements of the recommended check. If the base soil gradations vary substantially, such as might occur in a stratified foundation, it may not be possible to meet the recommended permeability check while also meeting the particle retention criterion. In such cases, it is essential that the particle retention criterion, D_{15Fmax}, be met. The designer then needs to assess the significance of not meeting the permeability check. If this could result in a condition where seepage flow could be partially blocked in a layer of base soil and pressure could build up, it would be appropriate to include a filter-compatible coarser drain layer immediately downstream of the filter to provide flow capacity. The writer experienced this problem in the dam safety modification of Washakie Dam, WY, as documented in France (2002).

Step 7. The maximum and minimum values of D_{60F} are established as follows:

- $D_{60Fmin} = D_{15Fmax}$
- $D_{60Fmax} = 5 \times D_{60Fmin}$

Step 8. The upper and lower particle size limits as are established as follows:

- The maximum particle size, $D_{100Fmax}$ = 2 inches (50.8 mm)
- There should be no more than 5% finer than the #200 sieve size for the compacted in-place material.

In addition, determine D_{90Fmax} from the table shown in Figure 6. For purposes of this determination, D_{10} in the table can be estimated as $D_{15Fmin}/1.2$, in this case $0.14/1.2 = 0.12$ mm. From Figure 6, this results in $D_{90Fmax} = 20$ mm.

Base Soil Category	If D_{10} is (mm)	Then Maximum D_{90} is, (mm)
ALL CATEGORIES	< 0.5	20
	0.5-1.0	25
	1.0-2.0	30
	2.0-5.0	40
	5.0-10	50
	> 10	60

NRCS, 1994/2017

Figure 6 Table for Selection of D_{90Fmax}

With the completion of Step 8, all seven control points have been determined, and gradation limits for the filter can be estimated as shown in Figure 7.

[4] Coefficient of curvature is defined as $C_z = D_{30}^2 / (D_{10} \times D_{60})$.

Filter specifications could be developed based on these limits, and any gradation within the limits would serve as an acceptable filter. However, following this approach could lead to a filter material that is expensive and difficult to produce. Commercially available gradations do not fit within the band shown in Figure 7, hence this would be a nonstandard gradation for commercial aggregate suppliers. If locally available material lies within the gradation band that would be fine. Also, if the filter was going to be produced on site, for example from a quarry for a new dam project, the band in Figure 7 may be able to be accommodated.

However, for relatively small filter quantities, for a rehabilitation project for example, it may be desirable to use a commercially available gradation. In Figure 8, the shaded area shows the specification limits for ASTM C-33 fine aggregate, a widely available commercial gradation. The limits for C-33 fine aggregate do not fall completely within the limits originally developed from the step-by-step process; however, C-33 fine aggregate meets all of the goals for filter design. First, and most importantly, it is finer than the calculated D_{15Fmax}, so it provides particle retention. Second, it meets the D_{15Fmin} requirement for permeability. Third, it is a uniform gradation, so it is not internally unstable. Finally, the upper limits of the gradation are not too coarse, so it is less susceptible to segregation, and the portion passing the #200 sieve is less than 5%.

The NRCS filter design guidance (NRCS, 1994/2017) includes the following two quotes that indicate the flexibility available to a designer:

> *Deviation from this guidance is acceptable based on sound engineering judgment ...*

> *However, in some cases, adjustments to the preliminary design band are made to accommodate standard readily available gradations.*

ASTM C-33 fine aggregate provides a good filter for many soils. It will meet filter design goals for all Category 2 soils, even if dispersive. D_{15max} for ASTM C-33 fine aggregate is less than 0.5 mm, which is the requirement for Category 2 dispersive soils. It might also serve as an acceptable filter for some Category 1 soils, depending on the regraded D_{85} value.

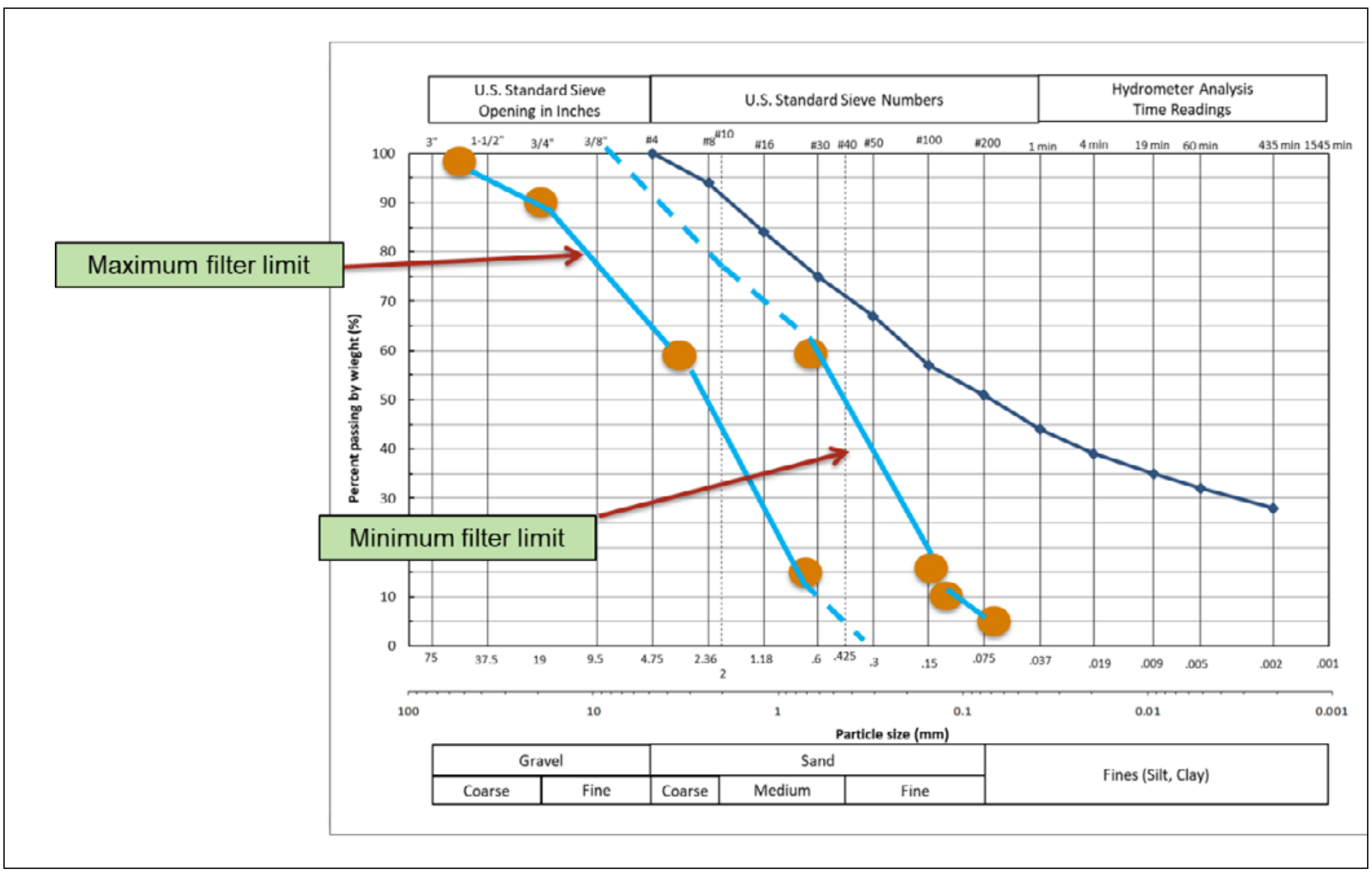

Figure 7 Control Points and Estimated Gradation Limits for Filter

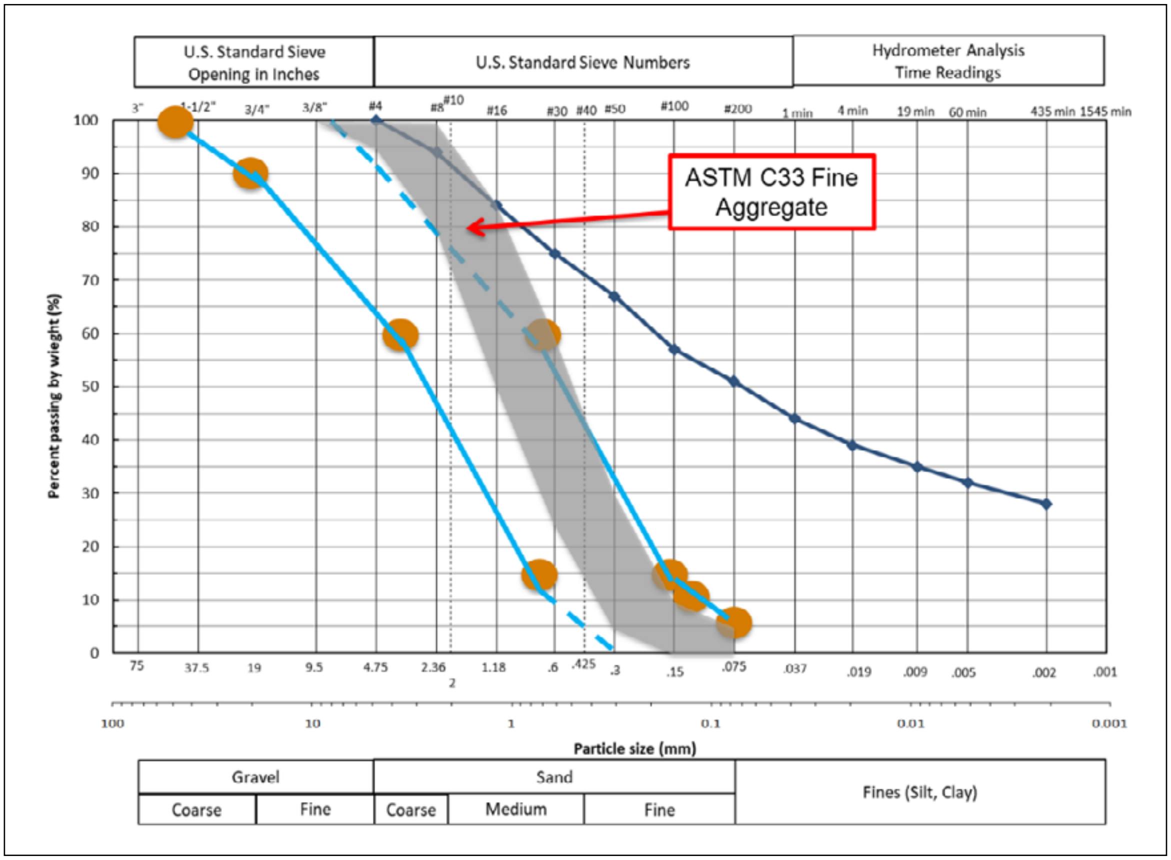

Figure 8 Comparison of Calculated Limits and C-33 Fine Aggregate

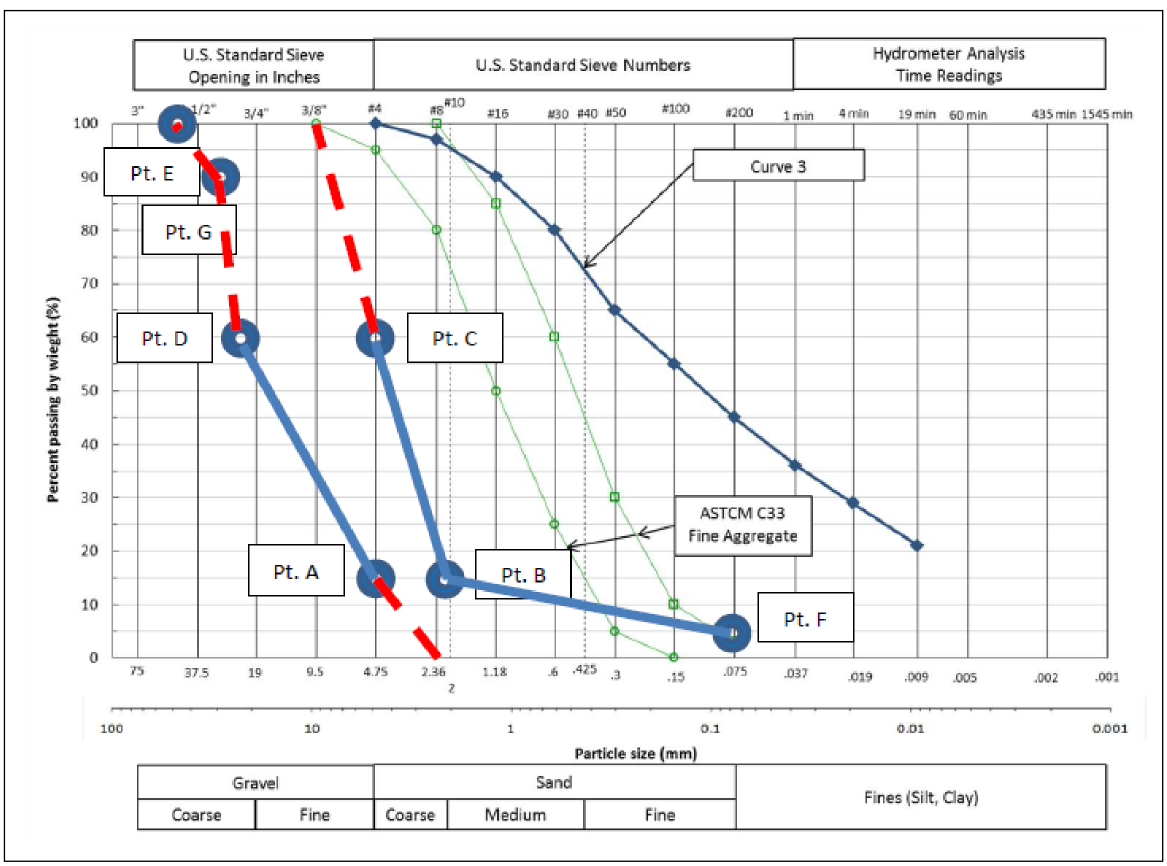

Figure 9 Filter Design for a Drain for a C-33 Fine Aggregate Filter

For a second, and final, example consider the design of a drain layer to be included in a two-stage embankment chimney filter/drain, a practice that the writer advocates. In this configuration, the filter is placed against the base soil (e.g., a core or a homogeneous embankment section) and the drain is placed against the filter. The writer advocates this configuration for several reasons including:

1. Limited contamination of the filter layer can be accommodated. If the filter layer is contaminated by fines, perhaps by a rainstorm, resulting in a reduction in vertical permeability, the interrupted vertical flow would be easily redirected into the drain.
2. Areas of concentrated seepage that might overwhelm the drainage capacity of the filter can be handled, because the drain will accommodate these increased flows.
3. Research completed by Reclamation and USACE demonstrated that a two-stage filter/drain was more likely to seal under flow if the filter was initially cracked (Reclamation, 2014).

Overall, the filter and drain system as a whole must be able to convey adequate discharge to dissipate pressures and gradients internal to the structure.

In the two-stage filter/drain configuration, the drain must function as a "filter" for the filter, and the same design goals apply. The step-by-step procedure will not be shown in detail here, but the following aspects of the procedure for this design are noted:

- Mathematical regrading is not required for C-33 fine aggregate, because it contains less than 15% finer than the #200 sieve, and it is neither gap graded nor broadly graded.
- C-33 fine aggregate is a Category 4 base soil (see Figure 5).

The results of the filter calculations for the drain are shown in Figure 9. Note that the coarse end of the gradation is being constrained by the 2-in. maximum particle size guidance. The guidance documents were really developed for design of filters for finer grained base soils, and some adjustments may need to be made for coarser filters, always guided by the goals of the filter design procedure.

In this case, the maximum particle size required could probably be relaxed to about 3 in. It also would be reasonable to look for commercially available sources that could meet the design goals, for example, AASHTO, ASTM, and state department of transportation standard gradations. However, it is always important to verify local availability of a standard gradation before it is selected for the specifications.

As filter and drain gradations become coarser, the problem illustrated in this example gets worse. The writer has seen some instances where the gradations of fine-grained cores and rockfill shells are so different that three or more layers are required. In fact, Terzaghi used a five-layer filter and drain system for the Bou Hanifa Dam referenced earlier in this article. In those cases, a designer should use his or her judgment in designing the coarser zones while meeting the fundamental goals of filter design.

CLOSURE

The current state of the practice procedures for soil filter gradation design are based on SCS/NRCS research published in the 1980s and incorporated in federal agency guidelines in the 1980s and 1990s. Filters designed prior to that time would most likely have been designed according to the Terzaghi filter criteria dating to the 1930s and also likely would not have been based on mathematically regraded base soil gradations, as included in the current practice. As a result, some of these earlier filters may not meet the current state of the practice criteria, particularly for clay and silt base soils, although some earlier designers may have wisely chosen to use ASTM C33 fine aggregate or similar gradations, which most likely are good filters.

All of the current filter design guidance documents include step-by-step procedures to determine control points that can be connected by interpolation and extrapolation to develop an initial range for filter gradation design. However, these procedures should not be applied in a cookbook approach. The designer should understand the purpose of each control point and the latitude available to the designer to adjust the points and the filter gradation range. The D_{15Fmax} control point is the critical point for particle retention, and it cannot be violated if the filter is to fulfill its primary function. There is some latitude for all of the other control points as long as the goals of filter design are achieved, namely, the filter (a) will retain the base soil under flow, (b) is sufficiently more permeable than the base soil, (c) is sufficiently uniform to prevent internal instability, and (d) does not have coarse particles that will promote segregation during transportation, handling, and placement. Cookbook application of the procedures can lead to filter gradations that are excessively expensive and difficult to produce, when more economical, readily available, commercially produced gradations would serve as good filters. ■

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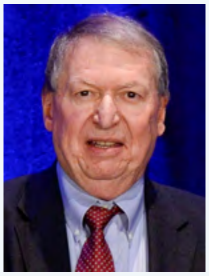

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