
Chapter 26

**Gradation Design of Sand
and Gravel Filters**

Issued August 2017

The U.S. Department of Agriculture (USDA) prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or a part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD). To file a complaint of discrimination, write to USDA, Director, Office of Civil Rights, 1400 Independence Avenue, SW., Washington, DC 20250-9410, or call (800) 795-3272 (voice) or (202) 720-6382 (TDD). USDA is an equal opportunity provider and employer.

Acknowledgments

The criteria Title 210, National Engineering Handbook (NEH), Part 633, Chapter 26, are based on the results of an extensive laboratory filter study carried out by the USDA's Natural Resources Conservation Service (NRCS) (formerly Soil Conservation Service (SCS)) at the Soil Mechanics Laboratory in Lincoln, NE from 1980 to 1985. The principals involved in this study were **Lorn P. Dunnigan**, SCS (deceased), **James R. Talbot**, SCS (retired), and **James L. Sherard**, consultant (deceased).

Revisions were developed in 1993 by **Danny K. McCook**, (deceased); **Charles H. McElroy**, (deceased); and **James R. Talbot**, national soils engineer, NRCS, Washington, DC (retired). **Danny McCook** developed the example problems.

Keith O. Grotrain, geotechnical engineer, National Design Construction Soil Mechanics Center, Lincoln, NE reviewed this chapter. The desktop publishing, editing, and illustrations of this chapter were provided by **Wendy Pierce**, Illustrator and **Suzi Self**, Editorial Assistant, Technical Publications Team, National Geospatial Center of Excellence (NGCE), NRCS, Fort Worth, TX.

Chapter 26

Gradation Design of Sand and Gravel Filters

Contents	633.2600 Purpose	26-1
	633.2601 Basic purpose of filters and drains	26-1
	633.2602 Permeability and capacity	26-2
	633.2603 Design objectives	26-2
	633.2604 Conventions for labels and definitions	26-3
	(a) Definitions	26-3
	633.2605 Procedures for determining filter gradation limits	26-4
	633.2606 References	26-8

Tables	Table 26-1	Base soil categories.....	26-4
	Table 26-2	Filtering criteria.....	26-6
	Table 26-3	Segregation criteria.....	26-7
	Table 26B-1	Grain-size distribution curve for category-1 soil (nondispersive).....	26B-1
	Table 26B-2	Specification table for ASTM C33 fine concrete aggregate.....	26B-3
	Table 26B-3	GSD chart for very fine category-1 soil—nondispersive	26B-4
	Table 26B-4	Filter band specifications for very fine category-1 soil—nondispersive	26B-6
	Table 26B-5	GSD chart for category-1 base soil —dispersive	26B-7
	Table 26B-6	Specification table using category-1 base soil—dispersive.....	26B-9
	Table 26B-7	GSD curve for sandy silt base soil.....	26B-10
	Table 26B-8	Specifications showing the requirements of ASTM C33 fine concrete aggregate	26B-12
	Table 26B-9	Filter design after adjusting design band to include ASTM C33 fine aggregate within the design	26B-12
	Table 26B-10	GSD curve for category-2 dispersive soil	26B-14
	Table 26B-11	Actual allowable filter gradations with category-2 soil—dispersive.....	26B-16
	Table 26B-12	GSD curve for sandy silt base soil.....	26B-17
	Table 26B-13	Specification using commonly specified sieve sizes for fine concrete aggregate	26B-19
	Table 26B-14	Category-3 soil with stable GSD	26B-21
	Table 26B-15	Specification table with specified sieve sizes for category 3 soil with stable GSD	26B-23
	Table 26B-16	Gradation for category-3 soil with design adjustments.....	26B-24
	Table 26B-17	Specification table using commonly specified sieve sizes	26B-26
	Table 26B-18	GSD category-4 soil	26B-27
	Table 26B-19	Specification table from the design band using commonly specified sieve sizes	26B-29
	Table 26B-20	GSD for category-4 soil with unstable portions of GSD	26B-30
	Table 26B-21	Specification table using commonly available sieve sizes	26B-33
Table 26B-22	Specification table with allowable filter gradation	26B-33	
Table 26B-23	Category-4 soil fine filter—design for coarse filter compatibility	26B-35	
Table 26B-24	Specification table for category-4 soil fine filter.....	26B-36	

Figures	Figure 26-1	Illustration of step-by-step procedure	26-5
	Figure 26A-1	Range of gradations of soils susceptible to internal instability	26A-2
	Figure 26A-2	Example of gap-graded soil gradation curve	26A-3
	Figure 26A-3	Double filter surrounding collector pipe	26A-4
	Figure 26A-4	Illustration of 35-percent passing guideline	26A-5
	Figure 26B-1	Gradation curve for category-1 soil—nondispersive	26B-1
	Figure 26B-2	Design filter band for category-1 soil—nondispersive.....	26B-3
	Figure 26B-3	Grain-size distribution curve category-1 soil—nondispersive	26B-4
	Figure 26B-4	Design filter band for very fine category-1 base soil—nondispersive.....	26B-6
	Figure 26B-5	Grain-sized distribution for category-1 soil—dispersive	26B-7
	Figure 26B-6	Design for category-1 base soil—dispersive	26B-9
	Figure 26B-7	Gradation curve for category-2 soil.....	26B-10
	Figure 26B-8	Alternative design filter for category-2 soil—nondispersive	26B-12
	Figure 26B-9	Alternative design filter for category-2 soil—nondispersive	26B-13
	Figure 26B-10	Gradation curve for category-2—dispersive soil	26B-14
	Figure 26B-11	Filter design for category-2 soil—dispersive	26B-16
	Figure 26B-12	Category-2 soil with regraded GSD—nondispersive.....	26B-17
	Figure 26B-13	Filter design of regraded curve category-2 soil—nondispersive	26B-19
	Figure 26B-14	Category 3 soil with stable GSD—nondispersive	26B-21
	Figure 26B-15	Design filter for category-3 soil with stable GSD—nondispersive fines....	26B-23
	Figure 26B-16	Category-3 soil—nondispersive fines.....	26B-24
	Figure 26B-17	Design filter for category-3 soil.....	26B-26
	Figure 26B-18	Category-4 base soil	26B-27
	Figure 26B-19	Design filter for category-4 base soil	26B-29
	Figure 26B-20	Category-4 soil with unstable GSD.....	26B-30
	Figure 26B-21	Design filter category-4 soil with unstable GSD	26B-32
	Figure 26B-22	Category-4 soil with unstable GSD alternative design	26B-33
	Figure 26B-23	Base soil for example 26B-11 is a fine filter design band, shown	26B-34
		with a minimum d_{85} size of 1.2 mm	
	Figure 26B-24	Preliminary design adjust D_{15}	26B-36
	Figure 26B-25	Preliminary design adjust D_{60}	26B-37

Figure 26B-26 Modified to limit segregation showing ASTM C33 sand 26B-38

Examples	Example 26B-1	Category-1 soil—nondispersive.....	26B-1
	Example 26B-2	Very fine category-1 soil—nondispersive.....	26B-4
	Example 26B-3	Category-1 soil—dispersive	26B-7
	Example 26B-4	Category-2 soil—nondispersive.....	26B-10
	Example 26B-5	Category-2 soil—dispersive	26B-14
	Example 26B-6	Category-2 soil after regrading of GSD—nondispersive	26B-17
	Example 26B-7	Category-3 soil with stable GSD and nondispersive fines.....	26B-21
	Example 26B-8	Category-3 soil with design adjustment	26B-24
	Example 26B-9	Category-4 base soil	26B-27
	Example 26B-10	Category-4 soil—unstable portions of GSD.....	26B-30
	Example 26B-11	Category-4 soil fine filter—design is for coarse filter compatibility	26B-34

633.2600 Purpose

Title 210, National Engineering Handbook (NEH), Part 633, Chapter 26 presents criteria for determining the grain-size distribution (GSD) of sand and gravel filters needed to prevent internal erosion or piping of soil in embankments or foundations of hydraulic structures. These criteria are based on results of an extensive laboratory filter study carried out by the Soil Conservation Service (SCS) at the Soil Mechanics Laboratory in Lincoln, NE, from 1980 to 1985 (See 210-NEH, Chapter 26, Section 633.2606, "References," for published reports).

633.2601 Basic purpose of filters and drains

Filters are placed in embankment zones, foundations, or other areas of hydraulic structures for two purposes:

- To intercept water flowing through cracks or openings in a base soil and block the movement of eroding soil particles into the filter. Soil particles are caught at the filter face, reducing the flow of water through cracks or openings and preventing further erosion and enlargement of the cracks or openings.
- To intercept water flowing through the pores of the base soil, allowing passage of the water while preventing movement of base soil particles. Without filters, piping of susceptible base soils can occur when seepage gradients or pressures are high enough to produce erosive discharge velocities in the base soil. The filter zone is generally placed upstream of the discharge point where sufficient confinement prevents uplift or blowout of the filter. Drains consist of sand, gravel, or a sand and gravel mixture placed in embankments, foundations, and backfill of hydraulic structures, or in other locations to reduce seepage pressure. A drain's most important design feature is its capacity to collect and carry water to a safe outlet at a low gradient or without pressure buildup. Drains are often used downstream of or in addition to a filter to provide outlet capacity. Combined filters and drains are commonly used. The filter is designed to function as a filter and as a drain.

633.2602 Permeability and capacity

The laboratory filter study clearly demonstrated that graded filters designed in accordance with these criteria will seal a crack. The sealing begins when water flows through a crack or opening and carries soil particles eroded from the sides of the openings. Eroding soil particles collect on the face of the filter and seal the crack at the interface. Any subsequent flow is through the pores of the soil. If filters are designed to intercept cracks, the permeability required in the filter zone should be based on the steady state seepage flow through the pores of the base soil alone. The hydraulic capacity of any cracks need not be considered in designing the filter because the cracks have been shown to seal.

Where saturated steady-state seepage flow will not develop, for instance, in dry dams for flood control having a normal drawdown time of 10 days or less, filter capacity need only be nominal. Filters designed either to protect against steady-state seepage or internal erosion through cracks must be thick enough to compensate for potential segregation and contamination of the filter zones during construction. They must also be thick enough that cracks cannot extend through the filter zone during any possible differential movements.

A zone of coarser materials immediately downstream or below the filter, or both, provides additional capacity to collect and convey seepage to a controlled outlet. In some cases, a strip drain is used, and in others a perforated collector pipe is employed to outlet the collected seepage. To prevent movement of the filter materials into the coarse drain materials, the coarse drain materials must be designed for the proper gradation using procedures in this subchapter. Perforations in collector pipes must also be sized properly to prevent movement of the coarse drain materials into the perforations.

633.2603 Design objectives

This chapter presents a step-by-step procedure for designing a filter zone for an embankment dam. The filter design may be for various purposes, including zones that are embankment chimney filters, various foundation filter and drainage zones, or the design may be for a material to filter and drain another filter zone. The primary goal in designing a filter is to determine a gradation that will satisfy current criteria to prevent the loss of particles from the protected base soil. At the same time, the recommended process should achieve the most permeable gradation possible while achieving the foremost goal of providing an effective filter.

The filter band achieved by the recommended design process has a relatively narrow width to limit the potential for a gap-graded filter being supplied, but the filter band is wide enough to be practical to manufacture and supply. The procedure achieves a relatively broad band of acceptable gradations for the filter being designed. If a designer wishes to provide a narrower band to achieve specific objectives more closely, appendix 26B of this chapter provides examples of how a designer may elect to use a narrower band than the procedures in this chapter achieve.

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. Deviation from this guidance is acceptable based on sound engineering judgment, project-specific analyses, and project-specific laboratory and field test data.

Designers of earthfill projects rely on geotechnical specialists to provide quality field and laboratory testing parameters and analyses to ensure a final product that meets all regulatory and generally accepted state-of-practice designs. However, the lack of codification in practice allows many items to slip past reviews and checks. By using a checklist of critical items, reviewers should be able to do a more credible job of ensuring quality designs are approved.

Reviewers should be aware that their job is not complete until the dam is constructed and past the first filling critical stage in its life. By ensuring that adequate inspection programs are in place, the probability of the long-term success of the project is improved.

633.2604 Conventions for labels and definitions

These conventions are used in descriptions used in this procedure. The soil for which the filter is being designed is termed the “base soil.” When referring to particle sizes for the base soil, a lower case “d” is used, such as d_{85} size. The term d_{85} size refers to the particle size where 85 percent of the total sample is smaller than that size particle. When referring to the filter being designed, the convention in this chapter is to use a capital letter “D.” So, when referring to the D_{15} of the filter, the reference is to the size of particle in the filter of which 15 percent of the total filter is smaller than that size particle. When designing a second filter to protect another filter, this can be confusing because the filter being protected then becomes the base soil for this design procedure, whereas it was the filter while it was being designed. Some prefer to use the additional designations of d_{85b} and D_{15F} to show this more clearly, but that convention is not used in these examples.

(a) Definitions

Base soil—The soil immediately adjacent to a filter or drainage zone through which water may pass. This movement of water may have a potential for moving particles from the base soil into or through the filter or drain materials.

d_{15} , d_{85} , and d_{100} sizes—Particle sizes (mm) corresponding respectively to 15, 85, and 100 percent finer by dry weight from the gradation curve of the base soil.

D_5 , D_{10} , D_{15} , D_{30} , D_{60} , D_{85} , D_{90} , and D_{100} sizes—Particle sizes (mm) corresponding to the 5, 10, 15, 30, 60, 85, 90, and 100 percent finer by dry weight from the gradation curve of the filter.

Gradation curve (grain-size distribution (GSD))—Plot of the distribution of particle sizes in a base soil or material used for filters or drains.

CU—Coefficient of Uniformity D_{60}/D_{10}

Drain—A designed pervious zone, layer, or other feature used to reduce seepage pressures and carry water.

Filter—Sand or sand and gravel having a gradation designed to prevent movement of soil particles from a base soil by flowing water. Guidance on design using geotextiles and other nonsoil filter materials is not included.

Fines—That portion of a soil finer than a No. 200 (0.075 mm) U.S. Standard sieve as explained in table 26–1.

Soil category—One of four types of base soil material based on the percentage finer than the No. 200 (0.075 mm) U.S. Standard sieve as explained in table 26–1.

633.2605 Procedures for determining filter gradation limits

Appendix 26A provides more detailed and expanded information of this chapter on the step-by-step procedures. Determine filter gradation limits using these steps (refer to fig. 26–1 for illustration):

Step 1 Plot the gradation curves (grain-size distribution) of the base soil materials. Determine if the base soils have dispersive clay content (appendix 26A, A–1 provides further explanation).

Step 2 Determine if the base soils have particles larger than the No. 4 sieve. At the same time, determine if the base soils are gap-graded and potentially subject to internal instability (see app. 26A, A–2 for further explanation).

(a) If the base soil has no gravel particles and is not gap-graded, proceed to step 4.

(b) If a base soil contains any particles larger than the No. 4 (4.75 mm) sieve, the soil should be regraded on the No. 4 sieve; proceed to step 3, with the following exceptions.

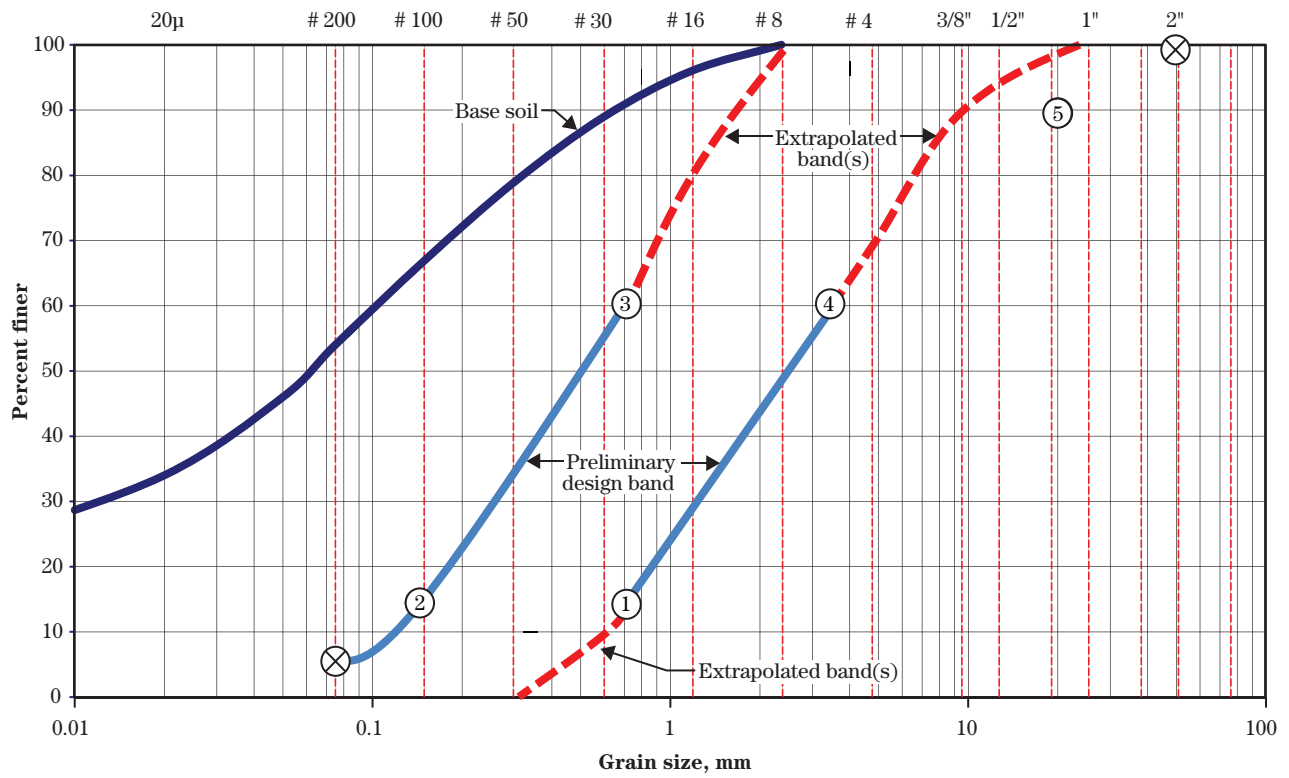
(1) Sands and gravels with less than 15 percent passing the No. 200 (0.075 mm) sieve that are not gap-graded and not broadly graded do not require regrading; proceed to step 4.

(2) Gap-graded soils should be regraded at the point of inflection where the curve inflects. Regrading procedures are similar to those in step 3, but rather than regrading on the No. 4 sieve, the regrading is done on

Table 26–1 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 silt and clays
2	40–85	Sands, silts, clays, and silty sands
3	15–39	Silty and clayey sands and gravels
4	< 15	Sands and gravels

Figure 26-1 Illustration of step-by-step procedure



the sieve closest to the upper size where the gradation curve inflects.

Step 3 Prepare adjusted gradation curves for base soils with particles larger than the No. 4 (4.75 mm) sieve, or on a smaller sieve if the soil has unstable portions in its gradation curve. Soils with less than 15 percent fines do not ordinarily require regrading (app. 26A, 26A-2).

- (a) Obtain a correction factor by dividing 100 by the percent passing the No. 4 (4.75 mm) sieve size (regraded or smaller sieve if applicable).
- (b) Multiply the percentage passing each sieve size of the base soil smaller than No. 4 (4.75 mm) sieve (or smaller sieve, if applicable) by the correction factor from step 3(a).
- (c) Plot these adjusted percentages to obtain a new gradation curve.
- (d) Use the adjusted curve to determine the percentage passing the No. 200 (0.075 mm) sieve to use in step 4.

Step 4 Place the base soil in a category based on the percent passing the No. 200 (0.075 mm) sieve from the regraded gradation curve data in accordance with table 26-1.

Step 5 To satisfy filtration requirements, determine the maximum allowable D_{15} size for the filter in accordance with table 26-2. The table uses the d_{85} of the base soil after the sample is regraded. (See fig. 26-1 point 1 and app. 26A, 26A-5 for further clarification of soils with dispersive fines.)

Step 6 Establish the minimum D_{15} of the filter as the greater of:

- 0.1 mm
- a fifth of the maximum D_{15} size established in step 5
- In some cases, this minimum D_{15} size may be too fine for adequate permeability, and the preliminary design band may need to be narrowed at this step by shifting the minimum D_{15} to be slightly coarser.

See figure 26-1, point 2 and appendix 26A, 26A-5 for a further description.

Step 7 Establish the minimum and maximum D_{60} sizes for the design filter band. This rationale is based on a maximum acceptable coefficient of uniformity (CU) value of 6 and a band width of 5. The minimum D_{60} size is equal to the maximum D_{15} size established in step 7. The maximum D_{60}

Table 26-2 Filtering criteria

Base soil category	Filtering—maximum D_{15}
1	The maximum D_{15} should be $\leq 9 \times d_{85}$ of the base soil, but not less than 0.2 mm, unless the soils are dispersive. Dispersive soils in category 1 require a filter with a maximum D_{15} that is ≤ 6.5 times the d_{85} of the base soil size, but not less than 0.2 mm.
2	The maximum D_{15} should be ≤ 0.7 mm unless soil is dispersive, in which case the maximum D_{15} should be < 0.5 mm.
3	The maximum D_{15} should be: $\leq \left(\frac{40 - A}{40 - 15} \right) \left[(4 \times d_{85}) - 0.7 \text{ mm}^* \right] + 0.7 \text{ mm}^*$ <p>A = percent passing No. 200 sieve after regrading (when $4 \times d_{85}$ is less than 0.7 mm*, use 0.7 mm*).</p>
4	The maximum D_{15} should be $\leq 4 \times d_{85}$ of base soil after regrading.

* If fines are dispersive, use 0.5 mm rather than 0.7 mm.

size is then five times the minimum D_{60} size. See figure 26–1, points 3 and 4.

To prevent gap graded filters

Both sides of the design filter band will have a CU defined as coefficient of uniformity = $D_{60} \div D_{10}$, equal to or less than 6. Initial design filter bands by this step will have CU values of 6. For final design, filter bands may be adjusted to a steeper configuration, with CU values less than 6, if needed. This is acceptable as long as other filter and permeability criteria are satisfied. Filters should not be designed with a CU value less than 2, as this would be a very poorly graded filter that could be subject to bulking, difficult to obtain, and difficult to compact. Initial bands are often steepened to accommodate the use of a standard commercially available gradation. Appendix 26A, 26A–12 has extensive additional descriptions of this step in the design of filters.

Step 8 The maximum particle size allowed is 2 inches and the maximum percentage passing the No. 200 sieve is 5 percent. Refer to appendix 26A, 26A–8 for additional guidance.

Step 9 To ensure that the filter cannot easily segregate during construction, the filter must not be overly broad in gradation. The relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. Calculate a preliminary minimum D_{10} size by dividing the minimum D_{15} size by 1.2. (This factor of 1.2 is based on the assumption that the slope of the line connecting D_{15} and D_{10} should be on a coefficient of uniformity of about 6.) Determine the maximum D_{90} . The coarse side of the design band must be finer than the maximum D_{90} . (See point 5 on fig. 26–1. See app. 26A, 26A–9 for the description.)

Step 10 Connect the minimum D_5 , D_{15} , and D_{60} sizes with a smooth curve to begin forming the fine side of the design band. Then, extrapolate the curve upwards smoothly, with a slightly convex shape to the D_{100} size. Connect the coarse control points, which are the maximum D_{15} and D_{60} control points, with a smooth curve. Extrapolate the curve upwards to an even D_{100} size that is equal to or smaller than the established maximum D_{100} size from step 8. Extrapolate the curve downwards from the maximum D_{15} size to the zero percent passing axis, intercepting the axis at a sieve size that will be used in writing specifications. Ensure

that the curve is finer than the maximum D_{90} size established in step 9. For purposes of writing specifications, select appropriate sieves and corresponding percent finer values that best reconstruct the design band and tabulate the values. See appendix 26A, 26A–10 for an illustration.

Step 11 The D_{50} of the surrounding filter must be larger than the perforation diameters or slot widths in a collector pipe installed in the filter. Perforations or slots should not be smaller than a quarter inch unless the pipe is surrounded with a gravel filter or a well-screen-type pipe is used with a slot size smaller than the criterion specified. See appendix 26A, 26A–11 for more detail.

Criteria for filters used adjacent to perforated collector pipe

Perforations or slots in pipes placed in the designed filter zone should be no larger than the smaller of the following:

- Half the d_{85} of the fine side of the filter
- The D_{50} size of the fine side of the filter

Step 12 The design band obtained in these steps is satisfactory to meet all the established filter and permeability requirements for a filter. However, in some cases, adjustments to the preliminary design band are made to accommodate standard readily available gradations. Appendix 26A, 26A–12 has additional information on adjusting the preliminary design band obtained in these steps to accommodate standard readily available gradations.

Table 26–3 Segregation criteria

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

Appendix 26B has numerous examples showing the application of these design procedures to a variety of base soils types.

633.2606 References

- Al-Hussaini, M.M. 1977. Contribution to the engineering soil classification of cohesionless soils. Misc. pap. S-77-21. U.S. Army Corps. of Engineers, Vicksburg, MS.
- Chapuis, R.P. 1992. Similarity of internal stability criteria for granular soils. *In* Canadian Geotechnical Journal 29, pp. 711-713.
- Foster, M.A. and R. Fell. 2001. Assessing embankment dams filters which do not satisfy design criteria. *J. Geotechnical and Geoenvironmental Engineering ASACE* vol 127. number 4 p. 398-407
- Sherard, J.L. 1979. Sinkholes in dams of coarse, broadly graded soils. Thirteenth International Congress on Large Dams, New Delhi, Vol. 2, pp. 25-35.
- Sherard, J.L. and L.P. Dunnigan. 1985. Filters and leakage control in embankment dams. *In* R.L. Volpe and W.E. Kelly (ed.). Seepage and leakage from dams and impoundments. Geotechnical Engineering Division Symposium Proceedings, Denver, CO, May 5, 1985. Amer. Soc. Civil Eng., New York, NY, pp. 1-30.
- Sherard, J.L., and L.P. Dunnigan. 1989. Critical filters for impervious soils. Amer. Soc. Civil Eng., Journal of Geotechnical Engineering, No. 115 (7). pp. 927-947.
- Sherard, J.L., L.P. Dunnigan, and J.R. Talbot. 1984. Basic properties of sand and gravel filters. Amer. Soc. Civil Eng., Journal of Geotechnical Engineering, No. 110 (6). pp. 684-700.
- Sherard, J.L., L.P. Dunnigan, and J.R. Talbot. 1984. Filters for silts and clays. Amer. Soc. Civil Eng., Journal of Geotechnical Engineering, No. 110 (6). pp. 701-718.
- Talbot, J.R., and D.C. Ralston. 1985. Earth dam seepage control, SCS experience. *In* R.L. Volpe and W.E. Kelly (ed.), Seepage and leakage from dams and impoundments. Geotechnical Engineering Division Symposium Proceedings, Denver, CO. Amer. Soc. Civil Eng., New York, NY, pp. 44-65.

Introduction

The procedures section in this document was intentionally kept as basic as possible for brevity and clarity of the design process. The basic steps may have some exceptions and some additional description is warranted to explain some of the steps in more detail. The purpose of this appendix is to provide those supplemental descriptions. This allows a simpler step-by-step process to be separated in the body of the document, with the auxiliary explanations provided in this appendix.

The following paragraphs are numbered according to the step in the procedure that is being explained more fully. Section A-1 explains step 1 in the design procedure.

A-1 Defining the base soil

The step-by-step filter design procedure assumes that a single gradation of base soil has been predetermined and a filter design is prepared for that gradation. More often, a number of gradations are generally obtained for any given zone for which a filter is being designed, rather than just a single gradation. Plotting several samples that represent the zone in which a filter is being designed on the same gradation sheet is a good visual tool that helps to determine the uniformity of the soils and whether the data includes anomalous gradations that may need special attention. Use enough samples to define the range of grain sizes for the base soil or soils.

For base soils with more than 15 percent passing the No. 200 sieve, adequate tests should be performed to establish whether the clay fines are dispersive in character. The crumb test and double hydrometer usually define this property adequately, but in some cases, pinhole and chemical tests may also be required. Generally, soils with a crumb dispersion rating of 2 or less and a double hydrometer percentage of dispersive clay less than 30 can be assumed to not contain sufficient dispersive clay to be problematic. 210-NEH, Part 633, Chapter 13, "Dispersive Clays," contains useful advice for sampling and testing for dispersive clays.

A-2 Additional considerations on regrading the base soil

Regrading samples with gravel particles on the No. 4 sieve is a standard practice that should always be followed. Very broadly graded gravelly soils and some gap-graded soils may be inherently unstable, with the finer particles being capable of moving internally within a matrix of larger particles. In some cases, very broadly graded and gap-graded soils should be regraded on a sieve finer than the No. 4 sieve. Additional information follows in the bulleted items.

An exception to the requirement for regrading gravelly soils on the No. 4 sieve is base soils that have less than 15 percent fines. These soils do not require regrading on the No. 4 sieve unless they are very broadly graded soils. See the following bullet for additional requirements for regrading broadly graded soils. The filter design process contains a thorough description of the mathematical process for regrading samples.

- **Regrading broadly graded soils**

Sherard (1979) described a unique type of problem that can occur with very broadly graded soils. These soil types may be susceptible to a process where fines in the soil can move within the matrix, and sinkholes can occur in embankments as a result of this movement. He studied soils susceptible to this phenomenon and determined a range of gradations of soils that experienced this problem. The red lines in figure 26A-1 reproduce the range of gradations Sherard found susceptible to the problem. Other authors have also described the problem of internal instability in broadly graded soils, and various methods have been presented for analyzing the nature of soils that should be considered susceptible. Chapuis (1992) analyzed the various methods for assessing internal stability, and distilled the guidance to a rule-of-thumb basis, which is shown with the blue lines in figure 26A-1. The blue lines represent a slope of 25 percent on the grain size plot. Chapuis demonstrated in his article that soils with portions of their gradation curve that are flatter than about 20 to 25 percent are susceptible to the problem of internal instability. Design example 26B-2 in appendix B incorporates this concept and demonstrates a broadly graded soil that should be regraded on a sieve other than the No. 4 sieve.

An overly broad gradation is considered to be one where the gradation curve on a semi-log plot has a slope (defined as the percent finer divided by the change in log of particle size), of flatter than 20 to 25 percent (a change of 20–25% passing over a log cycle of particle sizes). Gradation curves of base soils should be plotted on a graph that includes this defining line as shown in the examples in appendix B.

- **Gap-graded soils**

A potential problem with gap-graded soils is similar to that with very broadly graded soils. Finer particles may be moved by seepage forces internally within the soil matrix, leaving voids. To avoid this problem, filter design should protect finer fraction of the sample against movement, rather than the entire sample. Gap-graded base soils display a flat segment and an associated inflection in the gradation plot. Figure 26A–2 shows an example of a gap-graded soil. Filter designs that do not consider the nature of these soils may result in a filter that is too coarse to protect against

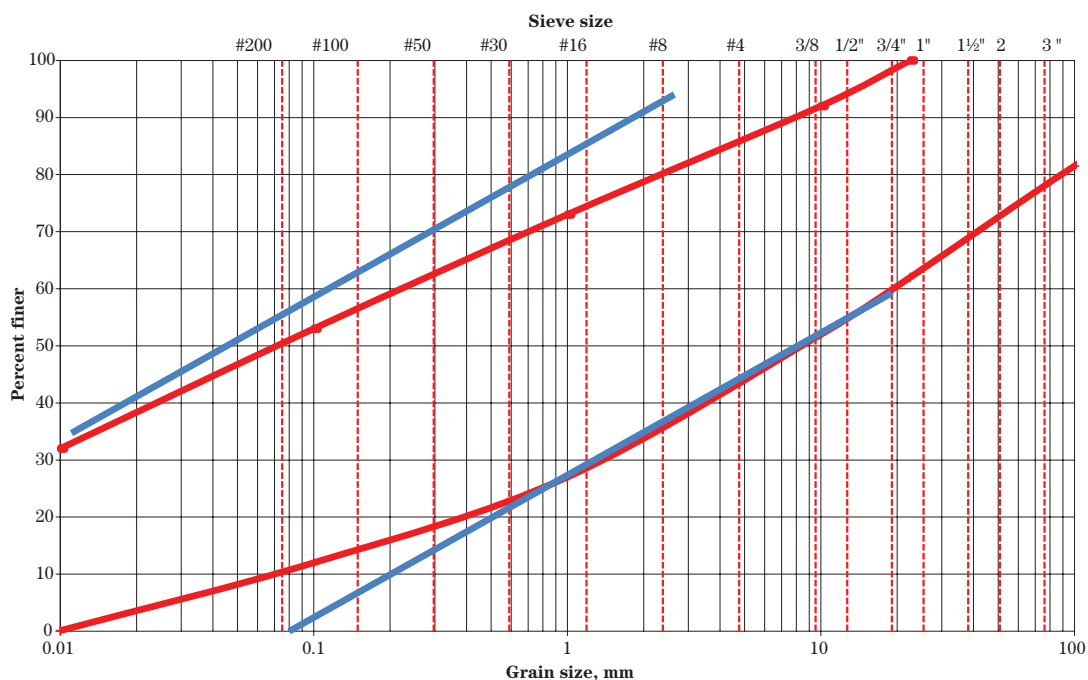
movement of the finer particles in the sample. Example 26–10 in appendix B shows a filter design for a gap-graded soil.

Regrading procedures are similar to those in step 3, but rather than regrading on the No. 4 sieve, the regrading is done on the sieve closest to the upper size where the gradation curve inflects. For the example soil shown in figure 26A–2, the regrading should be done on about the No. 16 sieve.

A–5 Modified criterion for dispersive clays

Foster and Fell (2001) recommended that filters protecting soils with dispersive clay fines should have a slightly more conservative filter criterion than for non-dispersive soils. This is a worthwhile modification of previous criteria and was incorporated into the recommended procedure for category-1, 2, and 3 soils. Category-4 soils have so few fines (less than 15%) that the dispersive character of the fines do not require special consideration. Several design examples in appendix B show how dispersive characteristics affect the design of several different categories of base soils.

Figure 26A–1 Range of gradations of soils susceptible to internal instability



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 and double hydrometer usually define this property adequately, but in some cases, pinhole and chemical tests may also be required. Generally, soils with a crumb dispersion rating of 1 or 2 and a double hydrometer percentage value less than 30 can be assumed to be nondispersive. Conversely, soils with a crumb test reading of 3 to 4 and a double hydrometer reading of 60 or more should be considered dispersive. 210-NEH, Part 633, Chapter 13, "Dispersive Clays," contains useful advice for sampling and testing for dispersive clays.

A-6 Additional information on permeability criterion

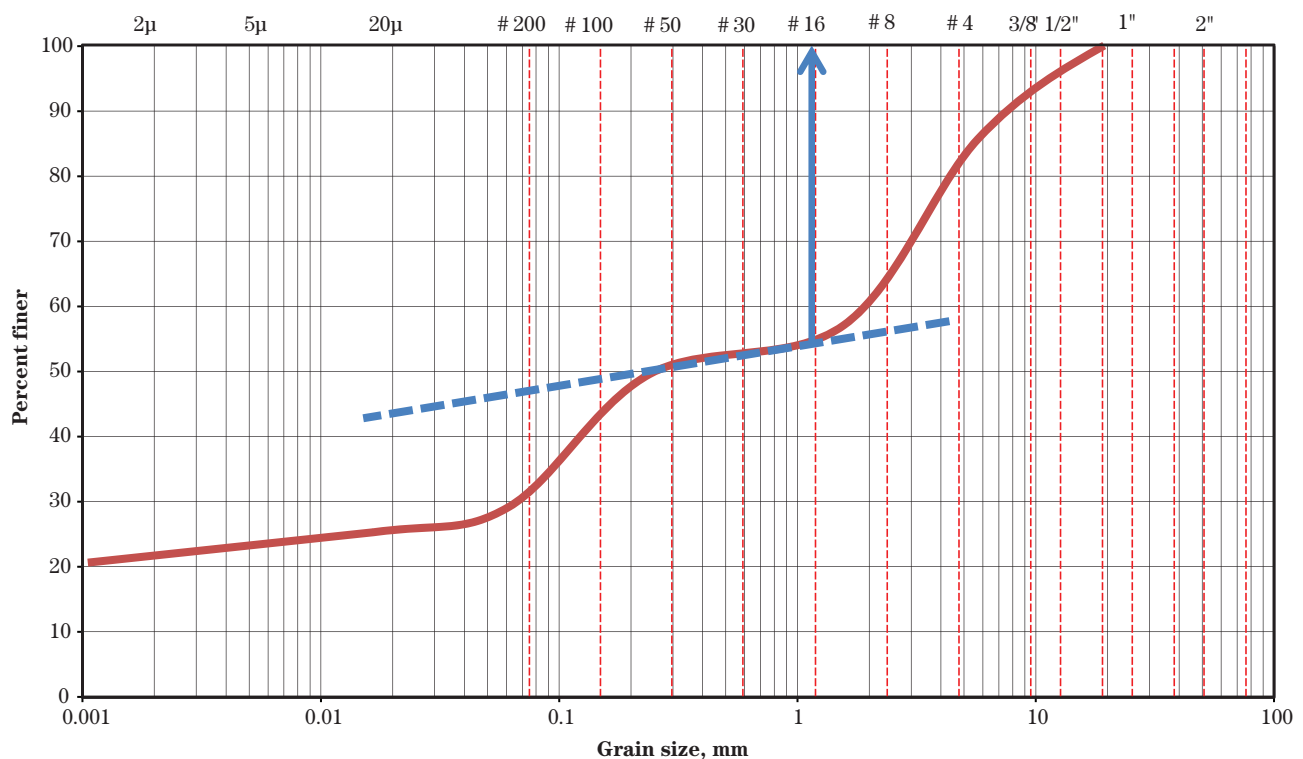
The design procedure provides a filter that protects against both intergranular seepage forces (backward erosion piping) and internal erosion of a crack in the base soil. The filter procedure establishes a minimum D_{15} size as equal to a fifth of the maximum D_{15} size

required for filtering. This minimum D_{15} size usually results in a filter that is permeable enough to provide good drainage of the base soil. To evaluate permeability further; however, a designer may also want to compare the minimum D_{15} size obtained in the procedure to the maximum d_{15} size of the base soil before regrading the base soil.

Permeability is directly proportional to the square of the effective grain size (all other factors being equal). If a filter's minimum D_{15} size is at least 4 to 5 times the d_{15} of the base soil, then the filter will have a permeability about 16 to 25 times that of the base soil. In some very broadly graded base soils, this requirement may be difficult to meet. For those cases, the maximum D_{15} size established to meet filter criterion and the minimum D_{15} to meet permeability criterion may result in an overly narrow filter band design.

In cases where the minimum and maximum D_{15} sizes obtained in previous steps, makes sides of the filter too close together to be practical for specifications,

Figure 26A-2 Example of gap-graded soil gradation curve



the necessity of meeting filter criterion should outweigh the permeability requirement. If widening the preliminary filter band is necessary, it is the minimum D_{15} size that should be moved, and not the maximum D_{15} size. In other words, filtering should always outweigh permeability in decisions regarding filter band design.

A-8 Supplemental considerations on maximum and minimum particle sizes

The filter design process allows filters to have a maximum of 5-percent fines. A designer may feel that a more restrictive requirement is needed in some cases. Designs requiring a maximum of 3-percent fines on filter materials delivered to the site and allowing then 5-percent fines in the placed filter zone are common. This allows the possibility of some breakdown of the filters during placement and compaction. Provisions for placement and compaction of filters are outside the scope of this document.

The maximum particle size in step 8 for all filters is 2 inches. However, for finer filters with small D_{10} sizes, the maximum particle size will essentially be controlled by the maximum D_{90} size. For instance, for filters that have a D_{10} size of less than 0.5 millimeter, the maximum allowable D_{90} size is 20 millimeters. With this restriction, the maximum particle size is essentially limited to about 25 millimeters or 1 inch.

The minus No. 40 (.425 mm) material for all filters must be nonplastic as determined in accordance with ASTM D4318. A supplemental test to qualify filters may be considered, the sand equivalent test (SEV). Sand for concrete is sometimes required to have a SEV value of 70 or higher.

A-9 Maximum D_{90} information

For the design of many fine filters, when the coarse side of the design band is extrapolated upwards with a slightly convex shape, the coarse D_{90} size of the design band and the maximum particle size that results will be considerably finer than is allowed by the criterion. For those cases, the criterion allowing a larger maximum D_{90} and maximum particle size criterion should be ignored and the design specifications should be based simply on the design band obtained in previous steps. Figure 26B-2 shows a filter design where this occurs. Examples 26B-1 through 26B-4 and several others in appendix B also illustrate designs where the band is considerably finer

than the maximum D_{90} and D_{100} size criterion allow. Example 26B-8 shows one case where the maximum D_{90} size restricts the design significantly.

A-10 Completing the preliminary design band

Step 10 in the filter design process describes how the initial control points plotted on a grain-size distribution graph are used to establish a filter design band. The process of extrapolating upwards and downwards from the established points is described narratively. Figure 26-1 illustrates step A-10 graphically.

A-11 Filter criterion for perforated and slotted pipe

The criterion in the body of this document addresses the compatibility of filters surrounding perforated or slotted collector pipes. The criterion usually applies to designs with a two-stage filter, where a fine filter is

Figure 26A-3 Double filter surrounding collector pipe



used next to the base soils in the foundation or embankment and a coarse filter is used surrounding the collector pipe. See figure 26A-3.

If a designer wishes to use a single finely graded filter surrounding a collector pipe, more stringent criteria are recommended. For this condition, two restrictions are recommended.

- First, slots should be used rather than perforations.
- Secondly, the slots in the pipe should be smaller than half of the d_{85} of the surrounding filter.

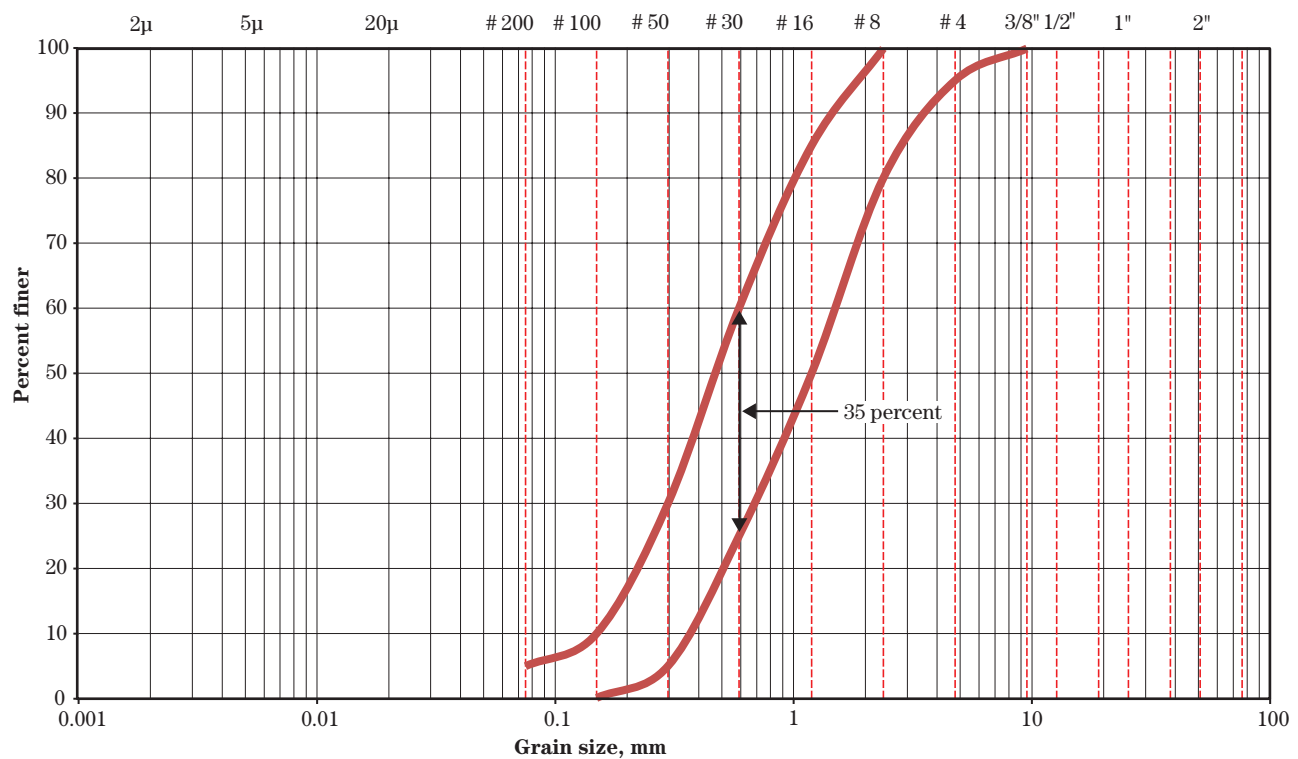
There is some research that indicates less plugging of the slots if the slot size is a fourth of the d_{85} of the surrounding filter.

A-12 Adjustments to preliminary design band

Step 7 of the procedure provides for a filter band design that is as well graded as considered advisable one with a CU (coefficient of uniformity $CU = D_{60}/D_{10}$) value of 6 for the preliminary design. More broadly graded filters would be susceptible to segregation and seldom should a filter have a flatter slope than allowed by this procedure.

However, in some cases, a more uniformly graded (more steeply graded curve) filter may be desired. Examples are cases where a standard commercial gradation is available that does not plot within the initial design band, but could fit if the design curve were adjusted to a steeper configuration. Other cases where adjustments may be desirable are those where onsite filters are available that are more uniformly graded than the preliminary filter design.

Figure 26A-4 Illustration of 35-percent passing guideline



In these cases, the filter limits that define the preliminary design band can be steepened to accommodate the more uniformly graded material. The filter band can be steepened, but not to the point where the CU is less than 2. In making the limits steeper, only the upper portion of the filter band above the D_{15} limits can be moved. The limits set for the D_{15} must remain as designed in step 5 to meet the filtering and permeability criteria. Several design examples in appendix B illustrate how adjustments can be made to the preliminary design band.

The requirements for coefficient of uniformity apply only to the coarse and fine limits of the design filter band individually. It is possible that an individual, acceptable filter whose gradation plots are completely within the specified limits could have a CU greater than 6 and still be acceptable. The design steps of this procedure will prevent use of gap-graded filters. It is not necessary to closely examine the coefficient of uniformity of a particular filter, as long as it plots within the design filter band.

Another requirement used by some engineers is to limit the maximum percentage change in percent passing for a given sieve to about 35 percent. This seems to be based on the shape of a commonly used material for fine filters, ASTM C33 fine concrete aggregate. As shown in the figure 26A-4, the percent finer range for sieves in the mid-range of the gradation of the sand is about 35 percent.

This requirement may be intended to prevent gap-graded filters, but a separate requirement prohibiting the use of gap-graded filters could also provide the same protection. This step-by-step procedure, which employs an initial CU value of 6 and a band width of 5, results in a maximum vertical change in percent passing for a given sieve of about 40 to 50 percent. This provides a wider band and results in considerable flexibility for suppliers to meet the specification. Using an overly restrictive specification range for filters may result in more difficulty meeting the specification and a higher cost for the increased precision in manufacturing the filter.

Appendix B

Example Filter Designs

Example 26B-1 Category-1 soil—nondispersive

Step 1 Plot the gradation curve(s), table 26B-1, of the grain-size distribution (GSD) (fig. 26B-1) of the base soil material(s). Determine if the base soils have dispersive clay content.

Assume that for this example, the soil has a plasticity index (PI) of 8, and the fines are not dispersive.

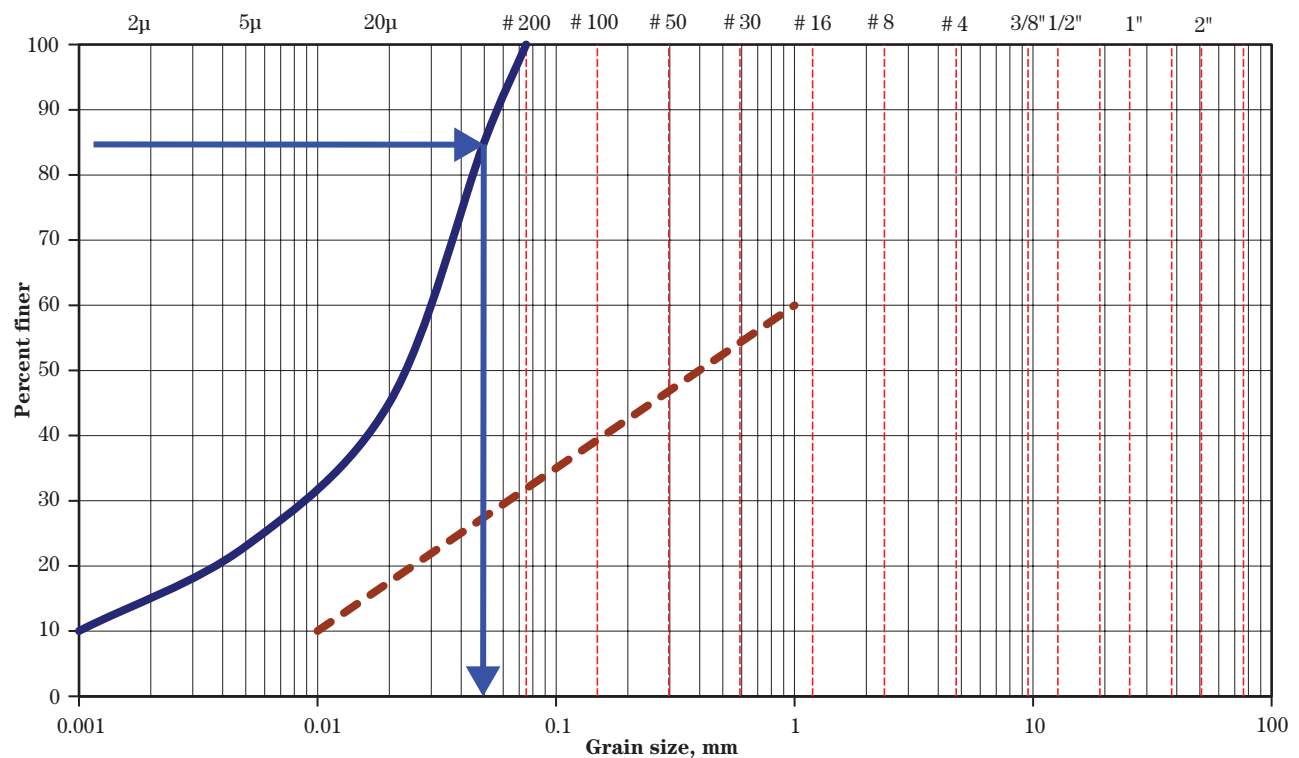
Step 2 Determine if the base soils have particles larger than the No. 4 sieve. At the same time, determine if the base soils are gap-graded and potentially subject to internal instability.

- If the base soil has no gravel particles, proceed to step 4.
- If a base soil contains any particles larger than the No. 4 sieve, the soil should be regraded on the No. 4 sieve (go to step 3), with the following exception.

Table 26B-1 Grain-size distribution curve for category-1 soil (nondispersive)

Sieve	Sieve size, mm	% finer
No. 200	0.075	100
0.05	0.05	85
0.02	0.02	45
0.005	0.005	23

Figure 26B-1 Gradation curve for category-1 soil—nondispersive



Example 26B-1 Category-1 soil—nondispersive—continued

— The gradation curve is seen by inspection not to have any particles larger than the No. 4 sieve, 4.76 millimeter. Also by inspection it can be seen that this soil is not gap graded when compared with the defining line included on the plot (refer to sec. A-2 in app. A for background of this procedure). Proceed to step 4.

Step 3: Skip this step because the base soil does not require regrading.

Step 4: Place the base soil in category 1 because the percent passing the No. 200 (0.075 mm) sieve is > 85 percent. Determine the d_{85} of the base soil is 0.05 millimeter.

Step 5: To satisfy filtration requirements, determine the maximum allowable D_{15} size for the filter. The table uses the d_{85} of the base soil after the sample is regraded.

Maximum $D_{15} \leq 9 \times d_{85}$, but not less than 0.2 millimeter.

Then the maximum D_{15} size is $\leq 9 \times 0.05$ millimeter ≤ 0.45 millimeter.

Step 6 Establish the minimum D_{15} of the filter as the greater of:

- 0.1 millimeter, or
- a fifth of the maximum D_{15} size established in step 5

Compute a fifth of the maximum D_{15} size ($0.45 \div 5 = 0.09$ mm). Use 0.1 millimeter as the minimum D_{15} size.

Step 7 Based on a CU value of 6 and a band width of 5, the minimum D_{60} size is equal to the maximum D_{15} size established in step 6. The maximum D_{60} size is then 5 times the minimum D_{60} size. Locate on a plot and label these two additional control points.

Step 8 The maximum particle size is 2 inches and the maximum percentage passing the No. 200 sieve is 5 percent.

Step 9 To ensure that the filter cannot easily segregate during construction, the filter must not be overly broad in gradation. The relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. Calculate a preliminary minimum D_{10} size by dividing the minimum D_{15} size by 1.2.

The minimum D_{15} size is 0.1 millimeter, so the minimum D_{10} size is less than 0.1 millimeter. According to the criterion table, the maximum D_{90} size for filters with a D_{10} size less than 0.5 millimeter is 20 millimeter. Ensure that the resulting design band does not exceed this point.

Step 10 Connect the fine control points to form a partial design for the fine side of the filter band. Connect the coarse control points to form a design for the coarse side of the filter band. Complete the design of the filter band by extrapolating the coarse and fine curves to the 100 percent finer value (fig. 26B-2). For purposes of writing specifications, select appropriate sieves and corresponding percent finer values that best reconstruct the design band and tabulate the values.

Additional design considerations

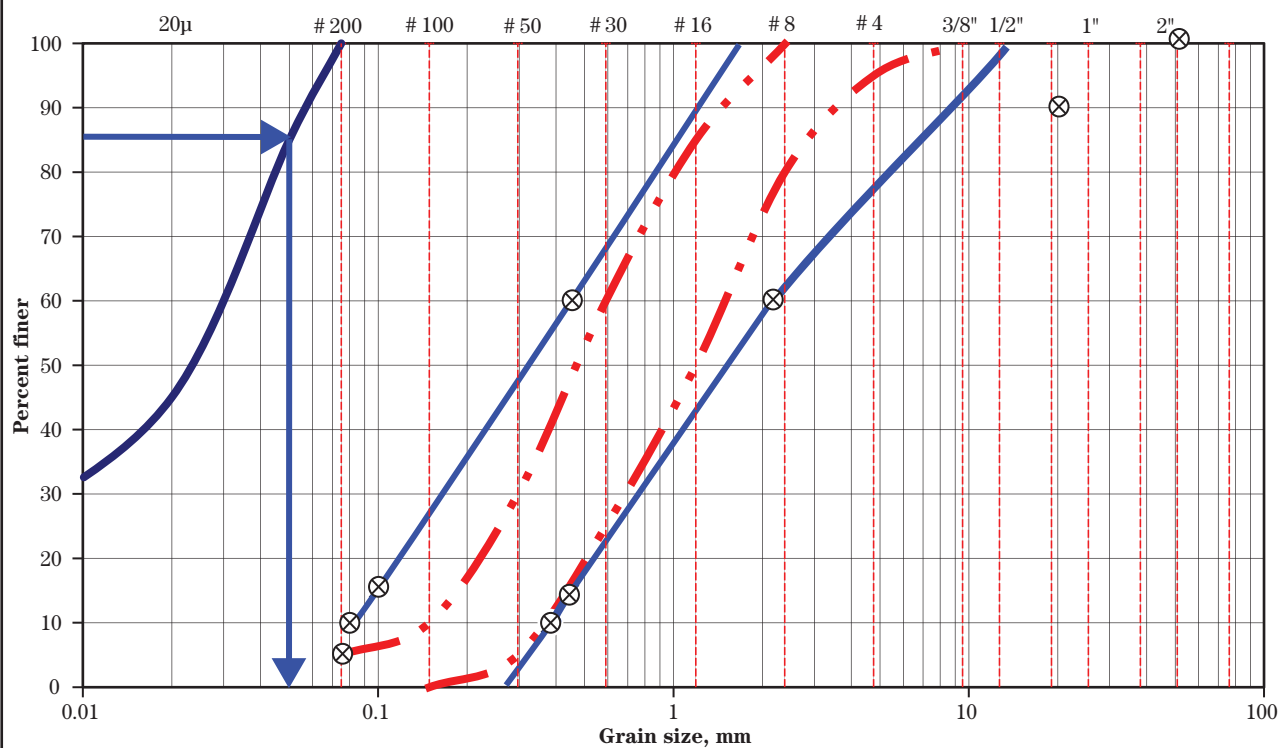
For this example, a standard, readily available gradation, ASTM C33 fine concrete aggregate, meets the design band. From the design band, using commonly specified sieve sizes, table 26B-2 could be prepared. Even though ASTM C33 sand meets this required gradation, by using the broader design band, more leeway is provided to a contractor in meeting the design specification, which could result in lower bid prices.

Example 26B-1 Category-1 soil—nondispersive—continued

Table 26B-2 Specification table for ASTM C33 fine concrete aggregate

Sieve name	Sieve size, mm	% finer
1/2 inch	12.7	100
3/8 inch	9.5	100
No. 4	4.76	95–100
No. 8	2.38	80–100
No. 16	1.19	50–85
No. 30	0.59	25–60
No. 50	0.297	5–30
No. 100	0.149	0–10
No. 200	0.075	0–5

Figure 26B-2 Design filter band for category-1 soil—nondispersive



Example 26B-2 Very fine category-1 soil—nondispersive

Step 1 Plot the gradation curves, table 26B-3, GSD of the base soil materials (fig. 26B-3). Determine if the base soils have dispersive clay content.

In table 26B-3, the soil is given to have a PI of 22 and is nondispersive.

Step 2 Determine if the base soils have particles larger than the No. 4 sieve. At the same time, determine if the base soils are gap-graded and potentially subject to internal instability.

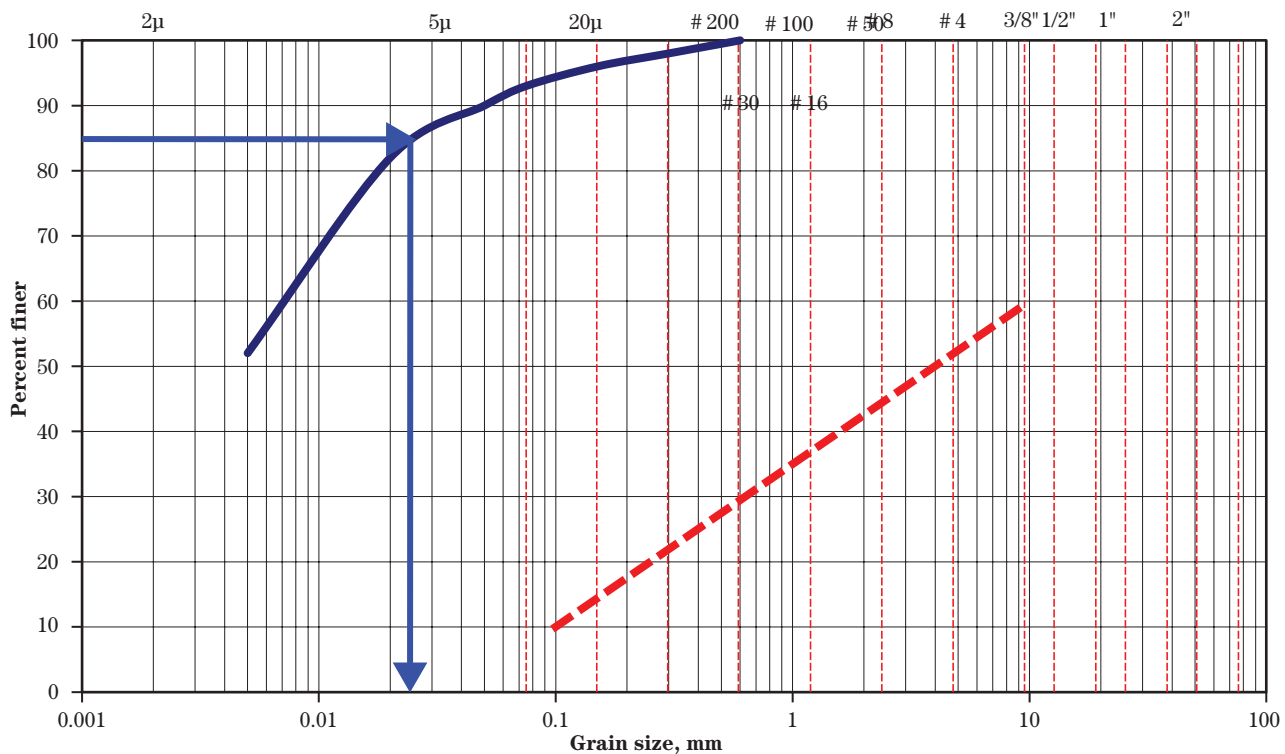
- If the base soil has no gravel particles, proceed to step 4.
- If a base soil contains any particles larger than the No. 4 sieve, the soil should be regraded on the No. 4 sieve.

Step 3 Skip this step because the base soil does not require regrading.

Table 26B-3 GSD chart for very fine category-1 soil—nondispersive

Sieve	Sieve size, mm	% finer
No. 30	0.600	100
No. 50	0.300	98
No. 100	0.150	96
No. 200	0.075	93
0.05 mm	0.050	90
0.02 mm	0.020	82
0.005 mm	0.005	52

Figure 26B-3 Grain-size distribution curve category-1 soil—nondispersive



Example 26B-2 Very fine category-1 soil—nondispersive—continued

Step 4 Place the base soil in category 1 based on the percent passing the No. 200 (0.075 mm) sieve of 93 percent being > 85 percent. Determine the d_{85} of the base soil to be 0.025 mm.

Step 5 To satisfy filtration requirements, determine the maximum allowable D_{15} size for the filter. The table uses the d_{85} of the base soil after the sample is regraded. Because the soil is not dispersive, use the criterion:

Maximum $D_{15} \leq 9 \times d_{85}$, but not less than 0.2 millimeter

Then the maximum D_{15} size is $\leq 9 \times 0.025$ millimeter ≤ 0.23 millimeter.

Step 6 Establish the minimum D_{15} of the filter as the greater of:

- 0.1 millimeter, or
- a fifth of the maximum D_{15} size established in step 5

Compute a fifth of the maximum D_{15} ($0.23 \div 5 = 0.04$ mm). Use 0.1 millimeter as the minimum D_{15} size.

Step 7 Based on a CU value of 6 and a band width of 5, the minimum D_{60} size is equal to the maximum D_{15} size established in step 6 of 0.23 millimeter. The maximum D_{60} size is then five times the minimum D_{60} size ($5 \times 0.23 = 1.15$ mm). Locate on a plot and label these two additional control points.

Step 8 Determine the minimum D_5 and maximum D_{100} sizes of the filter in accordance with the criteria table. Label these control points. The maximum particle size is 2 inches and the maximum percentage passing the No. 200 sieve is 5 percent.

Step 9 To ensure that the filter cannot easily segregate during construction, the filter must not be overly broad in gradation. The relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. Calculate a preliminary minimum D_{10} size by dividing the minimum D_{15} size by 1.2.

The minimum D_{15} size is 0.1 millimeter, so the minimum D_{10} size is less than 0.1 millimeter. According to the criteria table, the maximum D_{90} size for filters with a D_{10} size less than 0.5 millimeter is 20 millimeter. Ensure that the resulting design band does not exceed this point.

Step 10 Connect the fine control points to form a partial design for the fine side of the filter band. Connect the coarse control points to form a design for the coarse side of the filter band. Complete the design of the filter band by extrapolating the coarse and fine curves to the 100 percent finer value. Figure 26B-4 shows the completed design with control points labeled. For purposes of writing specifications, select appropriate sieves and corresponding percent finer values that best reconstruct the design band and tabulate the values.

Additional design considerations

For this example, a standard, readily available gradation, ASTM C33 fine concrete aggregate, does not plot within the design band. The design band is finer than C33, as shown on the following solution. A designer should use the plotted design filter and specify an acceptable filter band such as shown in table 26B-4.

Example 26B-2 Very fine category-1 soil—nondispersive—continued

Figure 26B-4 Design filter band for very fine category-1 base soil—nondispersive

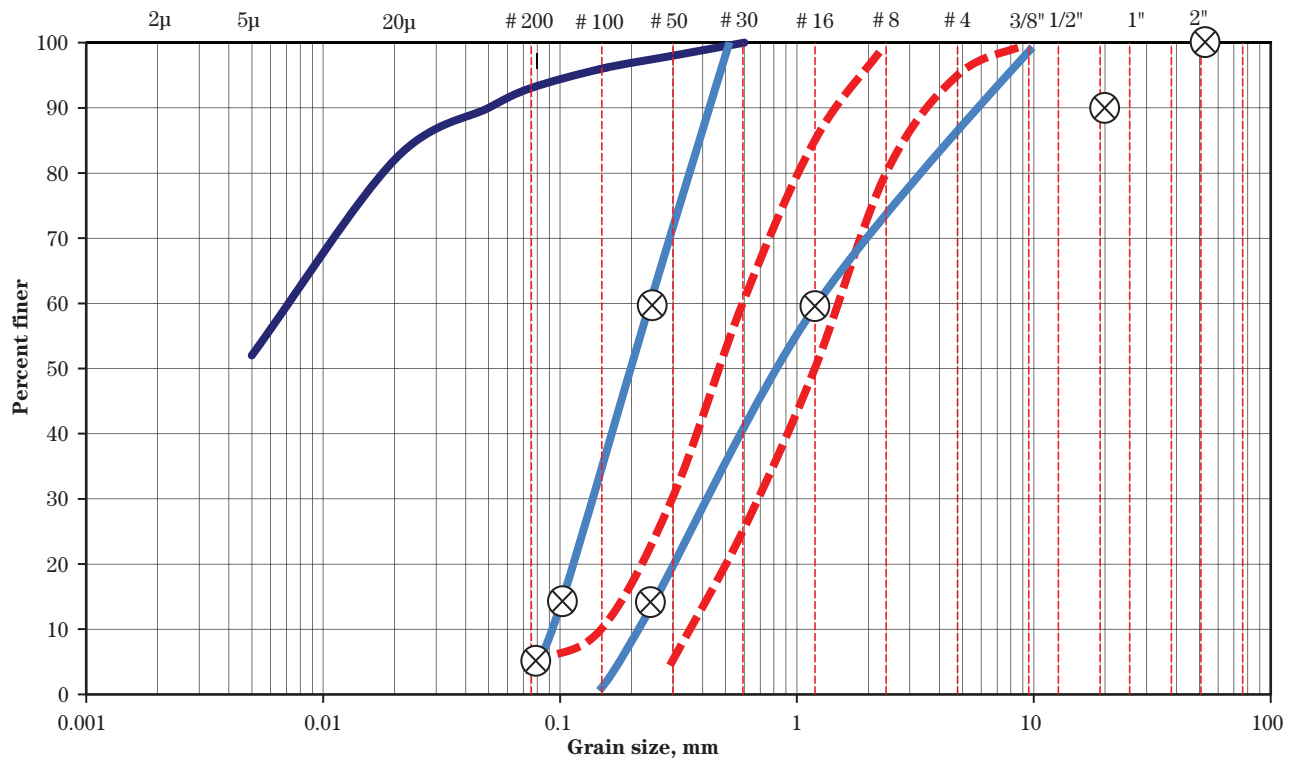


Table 26B-4 Filter band specifications for very fine category-1 soil—nondispersive

Sieve name	Sieve size, mm	% finer
No. 4	4.76	100
No. 8	2.38	90–100
No. 16	1.19	75–100
No. 30	0.59	50–100
No. 50	0.297	25–70
No. 100	0.149	5–30
No. 200	0.075	<5

Example 26B-3 Category-1 soil—dispersive

Step 1 Plot the gradation curves, table 26B-5, GSD of the base soil materials, figure 26B-5. Determine if the base soils have dispersive clay content.

In this design example, the soil is given to have a PI of 8 and the fines are dispersive.

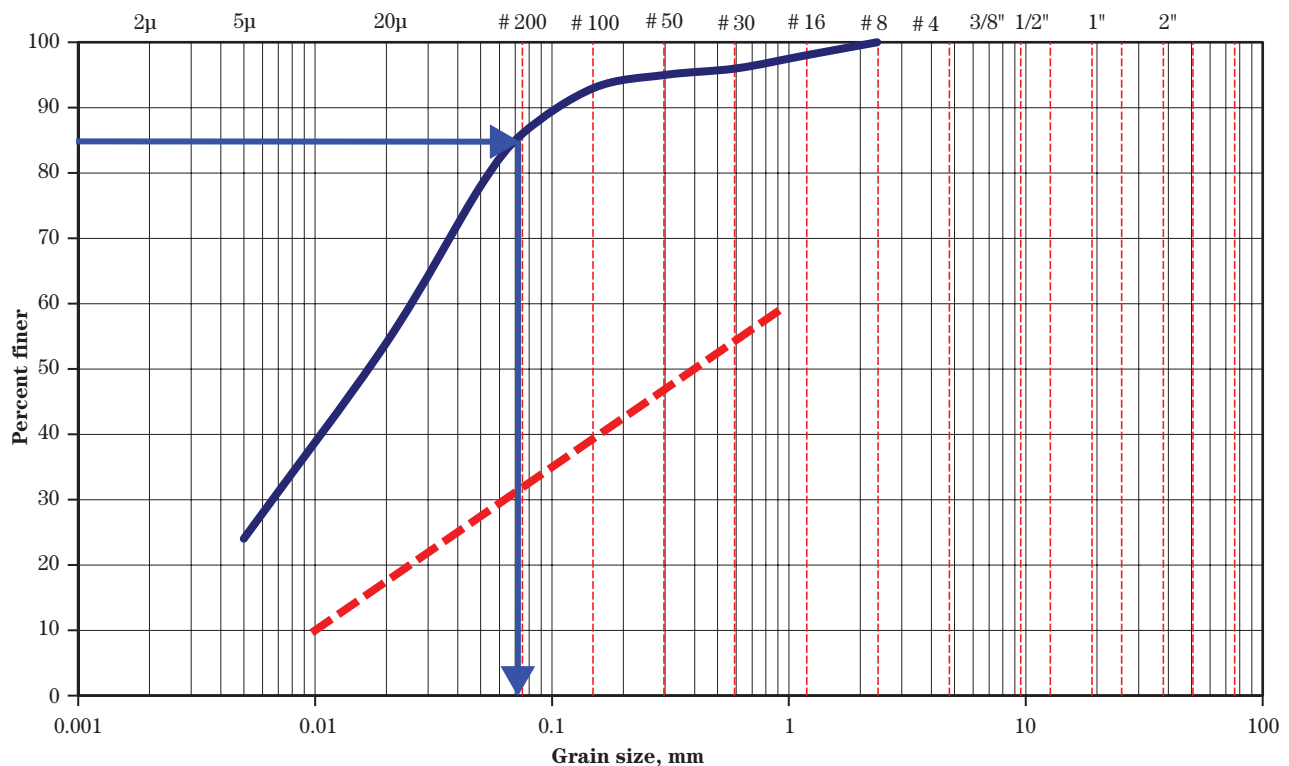
Step 2 Determine if the base soils have particles larger than the No. 4 sieve. At the same time, determine if the base soils are gap graded and potentially subject to internal instability.

- If the base soil has no gravel particles, proceed to step 4.
- If a base soil contains any particles larger than the No. 4 sieve, the soil should be regraded on the No. 4 sieve (go to step 3).

Table 26B-5 GSD chart for category-1 base soil — dispersive

Sieve	Sieve size, mm	% finer
No. 8	2.36	100
No. 16	1.18	98
No. 30	0.6	96
No. 50	0.3	95
No. 100	0.15	93
No. 200	0.075	86
0.05 mm	0.05	78
0.02 mm	0.02	54
0.005 mm	0.005	24

Figure 26B-5 Grain-size distribution for category-1 soil—dispersive



Example 26B-3 Category-1 soil—dispersive—continued

Step 3 Skip this step because the base soil does not require regrading.

Step 4 Place the base soil in category 1 based on the percent passing the No. 200 (0.075 mm) sieve of 86 percent being more than 85 percent. Determine the d_{85} of the soil to be 0.07 millimeter.

Step 5 To satisfy filtration requirements, determine the maximum allowable D_{15} size for the filter. The table uses the d_{85} of the base soil after the sample is regraded. Because the sample is given to have dispersive clay fines, the criterion is:

Maximum $D_{15} \leq 9 \times d_{85}$, but not less than 0.2 millimeter.

$$\text{Maximum } D_{15} \leq 6.5 \times 0.07 \text{ mm}, \leq 0.46 \text{ mm}$$

The maximum D_{15} size is then equal to 0.46 millimeter.

Step 6 Establish the minimum D_{15} of the filter as the greater of:

- 0.1 millimeter or
- a fifth of the maximum D_{15} size established in step 5

Compute a fifth of the maximum D_{15} size ($0.46 \div 5 = 0.092$ mm). Use 0.1 millimeter as the minimum D_{15} size.

Step 7 Based on a CU value of 6 and a band width of 5, the minimum D_{60} size is equal to the maximum D_{15} size established in step 5. The maximum D_{60} size is then five times the minimum D_{60} size ($5 \times 0.46 = 2.3$ mm). Locate on a plot and label these two additional control points.

Step 8 Determine the minimum D_5 and maximum D_{100} sizes of the filter in accordance with the criteria table. Label these control points. The maximum particle size is 2 inches and the maximum percentage passing the No. 200 sieve is 5 percent.

Step 9 To ensure that the filter cannot easily segregate during construction, the filter must not be overly broad in gradation. The relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. Calculate a preliminary minimum D_{10} size by dividing the minimum D_{15} size by 1.2.

The minimum D_{15} size is 0.1 millimeter, so the minimum D_{10} size is less than 0.1 millimeter. According to the criteria table, the maximum D_{90} size for filters with a D_{10} size less than 0.5 millimeter is 20 millimeter. Ensure that the resulting design band does not exceed this point.

Step 10 Connect the fine control points to form a partial design for the fine side of the filter band. Connect the coarse control points to form a design for the coarse side of the filter band. Complete the design of the filter band by extrapolating the coarse and fine curves to the 100 percent finer value. For purposes of writing specifications, select appropriate sieves and corresponding percent finer values that best reconstruct the design band and tabulate the values. The completed design with the important control points is shown in figure 26B-6.

Additional design considerations

Note that these steps provide a filter band design that is as well graded as possible and still meets criteria. This usually provides the most desirable filter characteristics. However, in some cases, a more uniform or more steeply graded filter band may be preferable. This usually occurs when it is desirable to obtain more readily available standard gradations or where it is desirable to use onsite materials for economy.

For this example, a standard, readily available gradation, ASTM C33 fine concrete aggregate meets the design band. A designer should specify a filter with the following allowable filter gradation and the specifications may state that ASTM C33 fine concrete aggregate falls within the specified limits of the filter band. From the design band, using commonly specified sieve sizes, specification table 26B-6 could be prepared.

Example 26B-3 Category-1 soil—dispersive—continued

Figure 26B-6 Design for category-1 base soil—dispersive

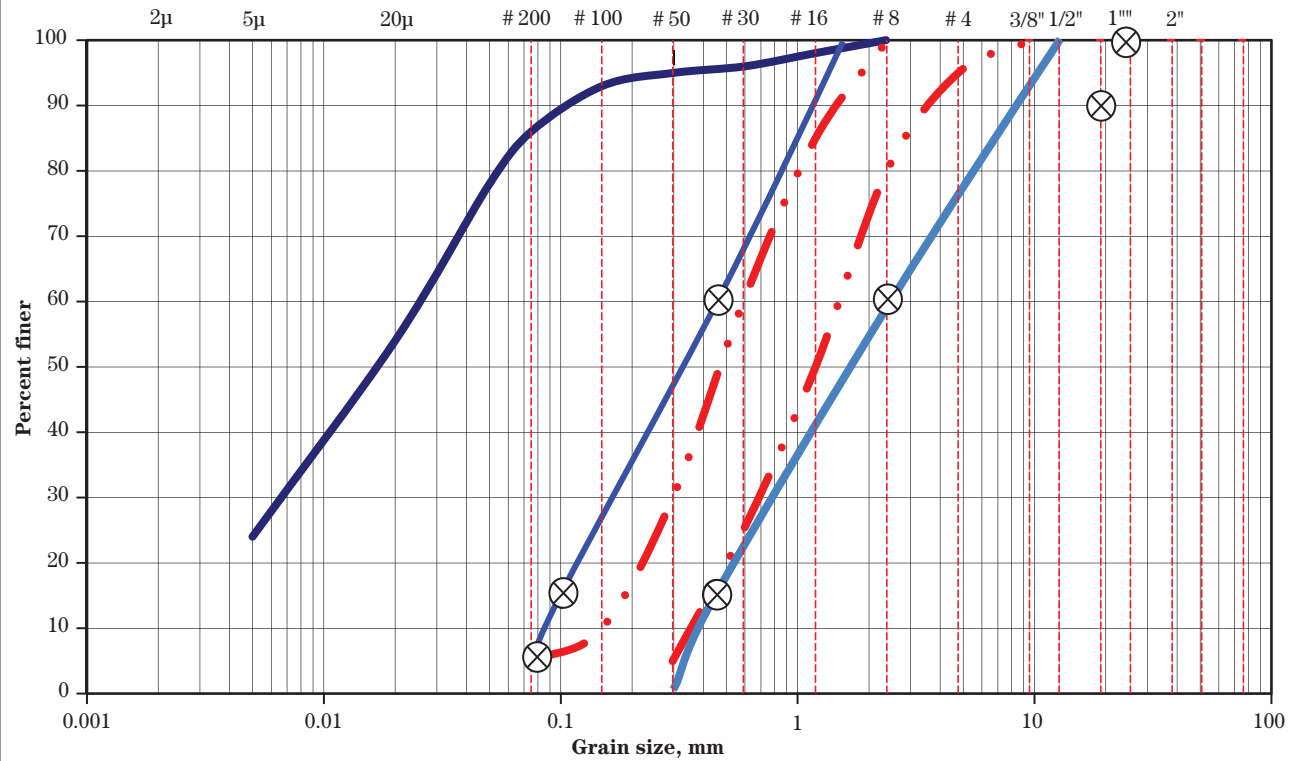


Table 26B-6 Specification table using category-1 base soil—dispersive

Sieve name	Sieve size, mm	% finer
3/8 inch	9.5	100
No. 4	4.76	90–100
No. 8	2.38	65–100
No. 16	1.19	40–90
No. 30	0.59	20–70
No. 50	0.297	10–40
No. 100	0.149	2–15
No. 200	0.075	< 5

Example 26B-4 Category-2 soil—nondispersive

Step 1 Plot the gradation curves, table 26B-7, GSD of the base soil materials (fig 26B-7). Determine if the base soils have dispersive clay content.

In this design example, the soil is given to have a PI of 8 and the fines are not dispersive.

Step 2 Determine if the base soils have particles larger than the No. 4 sieve. At the same time, determine if the base soils are gap-graded and potentially subject to internal instability.

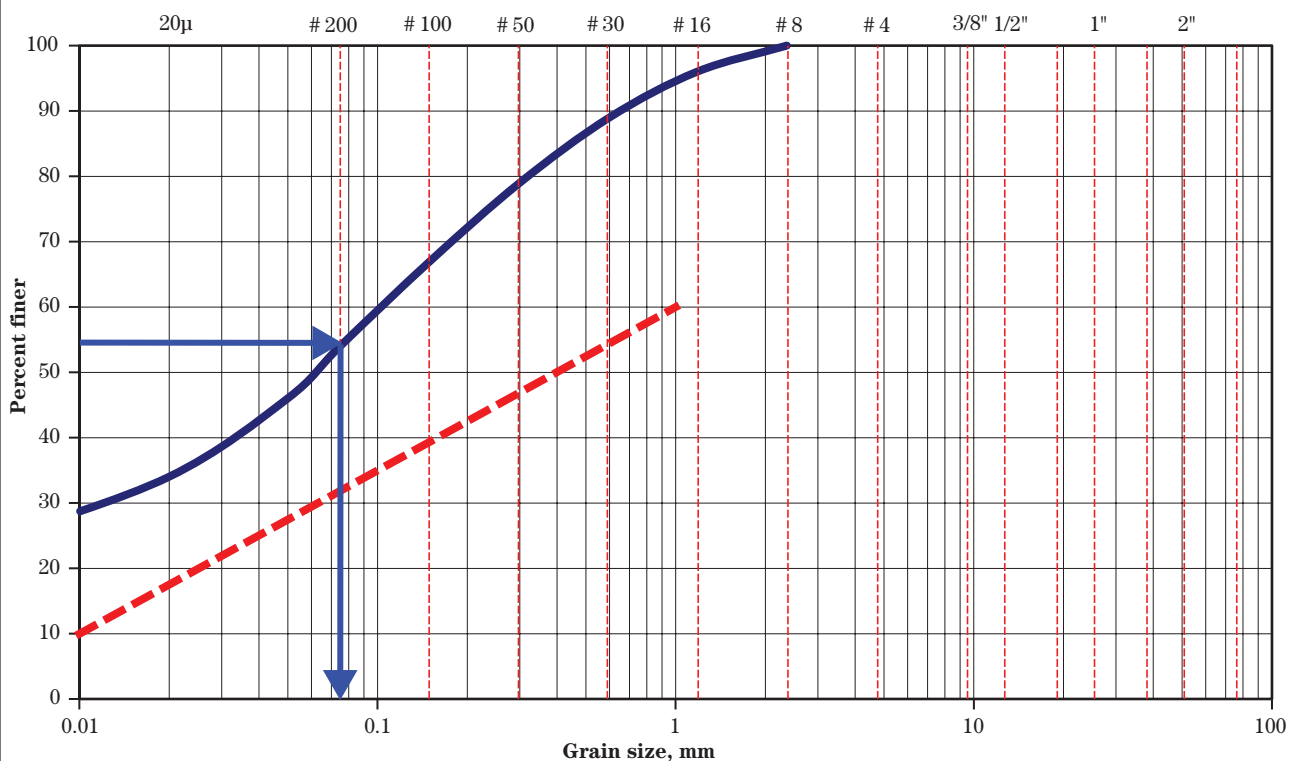
- If the base soil has no gravel particles, proceed to step 4.
- If a base soil contains any particles larger than the No. 4 sieve, the soil should be regraded on the No. 4 sieve (go to step 3).

Step 3 Skip this step because the base soil does not require regrading.

Table 26B-7 GSD curve for sandy silt base soil

Sieve	Size mm	% finer
No. 4	4.76	
No. 8	2.36	100
No. 16	1.18	96
No. 30	0.6	89
No. 50	0.3	79
No. 100	0.15	67
No. 200	0.075	54
0.05 mm	0.05	46
0.02 mm	0.02	34
0.005 mm	0.005	24

Figure 26B-7 Gradation curve for category-2 soil



Example 26B-4 Category-2 soil—nondispersive—continued

Step 4 Place the base soil in category 2 based on the percent passing the No. 200 (0.075 mm) sieve of 54 percent being between 40 and 85 percent.

Step 5 To satisfy filtration requirements, determine the maximum allowable D_{15} size for the filter. The table uses the d_{85} of the base soil after the sample is regraded.

The criteria chart shows that for category-2 soils that are not dispersive, the criterion for the maximum D_{15} is ≤ 0.7 millimeter.

Step 6 Establish the minimum D_{15} of the filter as the greater of:

- 0.1 millimeter or
- a fifth of the maximum D_{15} size established in step 5

Compute a fifth of the maximum D_{15} size ($0.7 \div 5 = 0.14$ mm). Use 0.14 millimeter as the minimum D_{15} size.

Step 7 Based on a CU value of 6 and a band width of 5, the minimum D_{60} size is equal to the maximum D_{15} size established in step 6, 0.7 millimeter. The maximum D_{60} size is then five times the minimum D_{60} size ($5 \times 0.7 = 3.5$ mm). Locate on a plot and label these two additional control points.

Step 8 Determine the minimum D_5 and maximum D_{100} sizes of the filter in accordance with the criteria table. Label these control points. The maximum particle size is 2 inches, and the maximum percentage passing the No. 200 sieve is 5 percent.

Step 9 To ensure that the filter cannot easily segregate during construction, the filter must not be overly broad in gradation. The relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. Calculate a preliminary minimum D_{10} size by dividing the minimum D_{15} size by 1.2.

The minimum D_{15} size is 0.14 millimeter, so the minimum D_{10} size is less than 0.12 millimeter. According to the criteria table, the maximum D_{90} size

for filters with a D_{10} size less than 0.5 millimeter is 20 millimeter. Ensure that the resulting design band does not exceed this point.

Step 10 Connect the fine control points to form a partial design for the fine side of the filter band. Connect the coarse control points to form a design for the coarse side of the filter band. Complete the design of the filter band by extrapolating the coarse and fine curves to the 100 percent finer value. The completed design band is shown in figure 26B-8, with the important control points shown. For purposes of writing specifications, select appropriate sieves and corresponding percent finer values that best reconstruct the design band and tabulate the values.

Additional design considerations

Note that these steps provide a filter band design that is as well graded as possible and still meets criteria. This usually provides the most desirable filter characteristics. However, in some cases, a more uniform or more steeply graded filter band may be preferable. This usually occurs when it is desirable to obtain more readily available standard gradations or where it is desirable to use onsite materials for economy.

For this example, a standard, readily available gradation, ASTM C33 fine concrete aggregate does not plot within the initial design band. An alternative design is to shift the minimum and maximum D_{60} sizes to the fine side to incorporate C33 within the design band.

Check the coefficient of uniformity of the shifted design by computing a new D_{60}/D_{10} ratio for the fine side of the band. The new D_{60} value is 0.45 and the new D_{10} size for the fine side is 0.12, so the new CU value is 3.80 ($45 \div 0.12$). This is greater than 2, so it is acceptable. A designer could merely specify that the filter supplied meet the requirements of C33 fine concrete aggregate, or a table with the actual allowable filter gradations on it could be prepared. From the design band, using commonly specified sieve sizes, table 26B-8 is prepared. Table 26B-9 is the filter design after adjusting design band to include C33 fine aggregate within the design.

Example 26B-4 Category-2 soil—nondispersive—continued

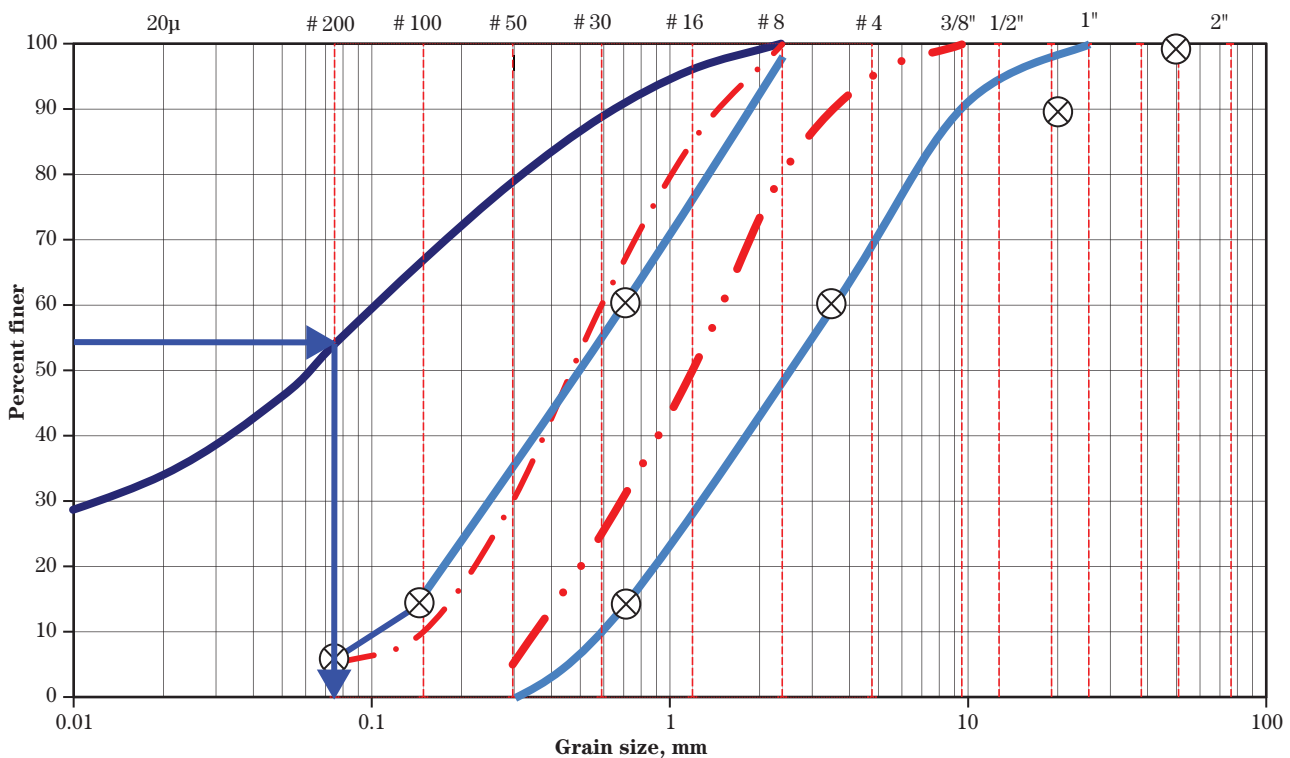
Table 26B-8 Specifications showing the requirements of ASTM C33 fine concrete aggregate

Sieve name	Sieve size, mm	% finer
3/8 inch	9.52	90–100
No. 4	4.76	70–100
No. 8	2.38	50–90
No. 16	1.19	30–75
No. 30	0.59	15–55
No. 50	0.297	50–35
No. 100	0.149	≤ 15
No. 200	0.075	≤ 5

Table 26B-9 Filter design after adjusting design band to include ASTM C33 fine aggregate within the design

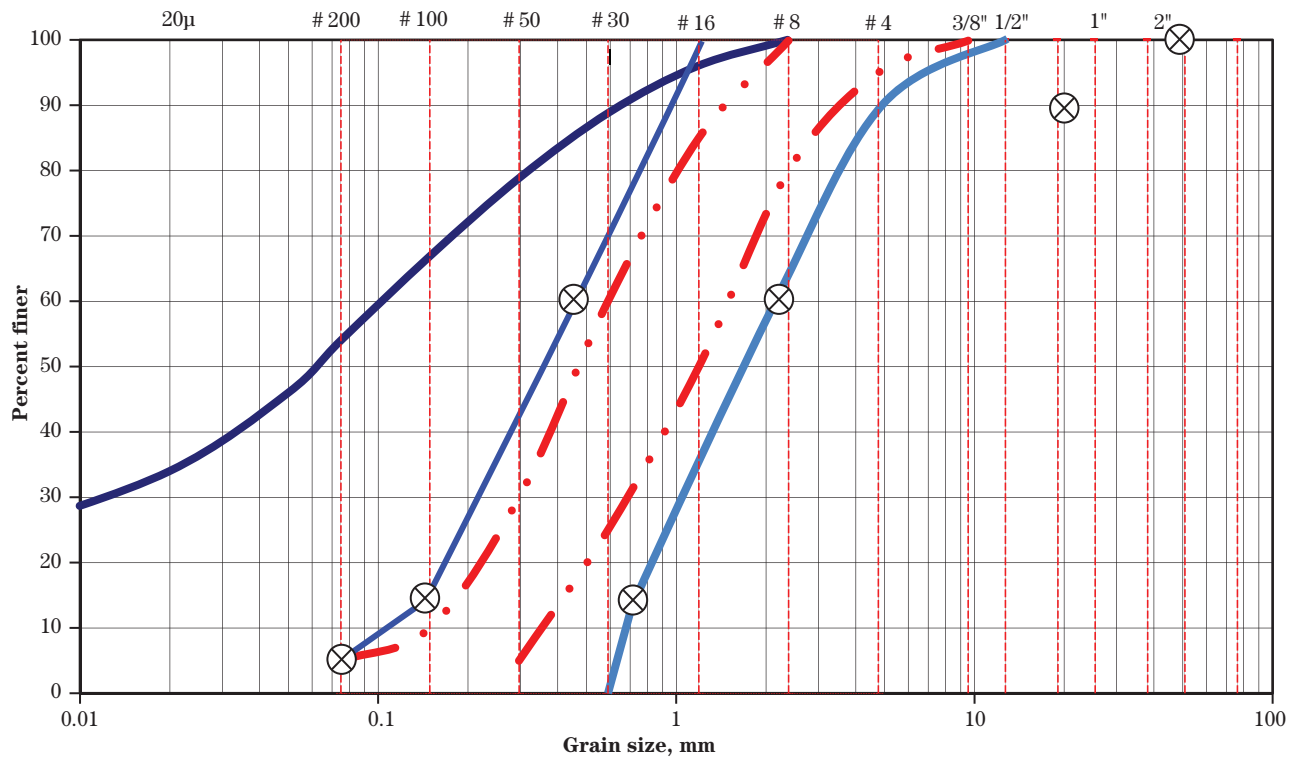
Sieve name	Sieve size, mm	% finer
3/8 inch	9.52	100
No. 4	4.76	90–100
No. 8	2.38	60–100
No. 16	1.19	40–100
No. 30	0.59	20–80
No. 50	0.297	10–40
No. 100	0.149	≤ 15
No. 200	0.075	≤ 5

Figure 26B-8 Alternative design filter for category-2 soil—nondispersive



Example 26B-4 Category-2 soil—nondispersive—continued

Figure 26B-9 Alternative design filter for category-2 soil—nondispersive



Example 26B-5 Category-2 soil—dispersive

Step 1 Plot the gradation curves, table 26B-10, GSD of the base soil materials (fig. 26B-10). Determine if the base soils have dispersive clay content.

The soil is given to have a PI of 8 and the fines are dispersive.

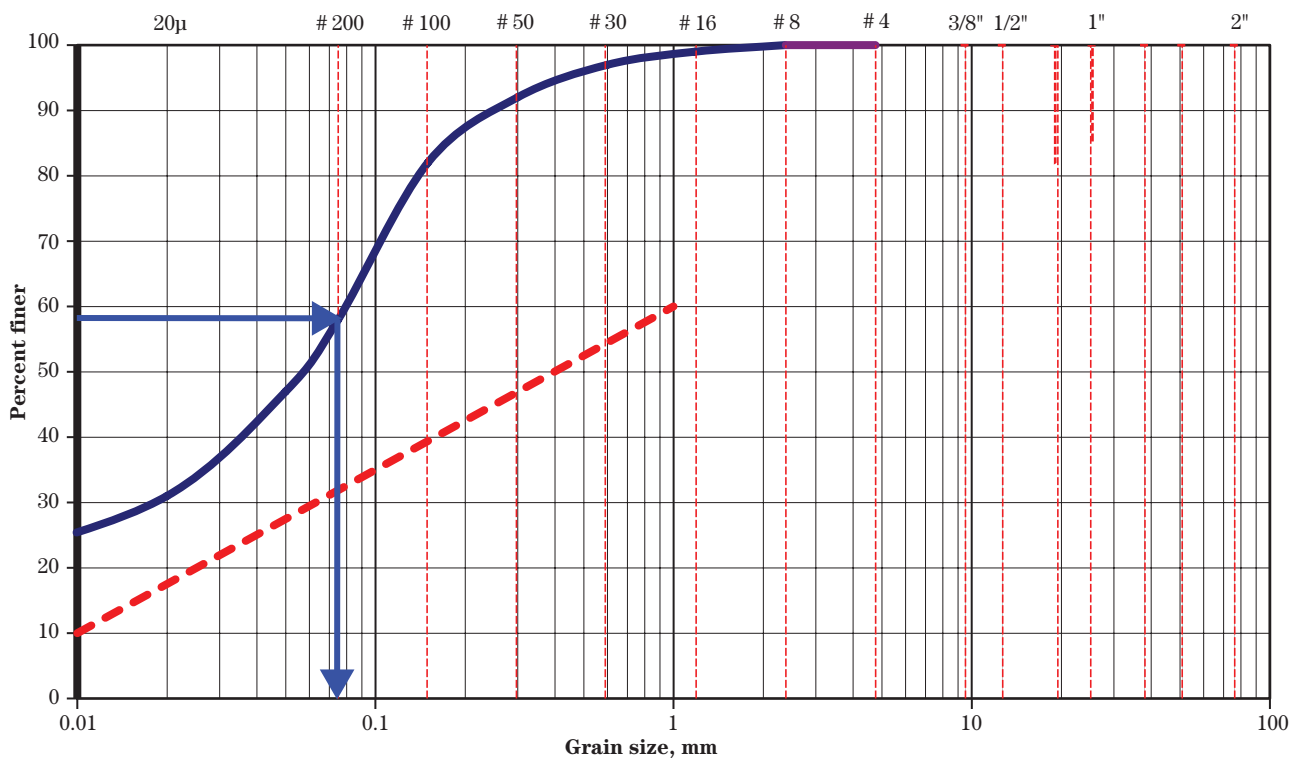
Step 2 Determine if the base soils have particles larger than the No. 4 sieve. At the same time, determine if the base soils are gap-graded and potentially subject to internal instability.

- If the base soil has no gravel particles, proceed to step 4.
- If a base soil contains any particles larger than the No. 4 sieve, the soil should be regraded on the No. 4 sieve (go to step 3).

Table 26B-10 GSD curve for category-2 dispersive soil

Sieve	Size mm	% finer
No. 8	2.36	100
No. 16	1.18	99
No. 30	0.6	97
No. 50	0.3	92
No. 100	0.15	82
No. 200	0.075	58
0.05	0.05	47
0.02	0.02	31
0.005	0.005	21

Figure 26B-10 Gradation curve for category-2—dispersive soil



Example 26B-5 Category-2 soil—dispersive—continued

Step 3 Skip this step because the base soil does not require regrading.

Step 4 Place the base soil in category 2 based on the percent passing the No. 200 (0.075 mm) sieve of 58 percent being between 40 and 85 percent.

Step 5 To satisfy filtration requirements, determine the maximum allowable D_{15} size for the filter.

The criterion table shows that for category 2 soils with dispersive clay fines, the criterion for the maximum D_{15} is maximum $D_{15} \leq 0.5$ millimeter.

Step 6 Establish the minimum D_{15} of the filter as the greater of:

- 0.1 millimeter, or
- a fifth of the maximum D_{15} size established in step 5

Compute a fifth of the maximum D_{15} size ($0.5 \div 5 = 0.1$ mm). Use 0.1 millimeter as the minimum D_{15} size.

Step 7 Based on a CU value of 6 and a band width of 5, the minimum D_{60} size is equal to the maximum D_{15} size established in step 5. The maximum D_{60} size is then five times the minimum D_{60} size ($5 \times 0.5 = 2.5$ mm). Locate on a plot and label these two additional control points.

Step 8 Determine the minimum D_5 and maximum D_{100} sizes of the filter in accordance with the criteria table. Label these control points. The maximum particle size is 2 inches and the maximum percentage passing the No. 200 sieve is 5 percent.

Step 9 To ensure that the filter cannot easily segregate during construction, the filter must not be overly broad in gradation. The relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. Calculate a preliminary minimum D_{10} size by dividing the minimum D_{15} size by 1.2.

The minimum D_{15} size is 0.1 millimeter, so the minimum D_{10} size is less than 0.1 millimeter. According to the criteria table, the maximum D_{90} size for filters with a D_{10} size less than 0.5 millimeter is 20 millimeter. Ensure that the resulting design band does not exceed this point.

Step 10 Connect the fine control points to form a partial design for the fine side of the filter band. Connect the coarse control points to form a design for the coarse side of the filter band. Complete the design of the filter band by extrapolating the coarse and fine curves to the 100 percent finer value. Figure 26B-11 shows the completed design with the important control points also shown. For purposes of writing specifications, select appropriate sieves and corresponding percent finer values that best reconstruct the design band and tabulate the values.

Additional design considerations

Note that these steps provide a filter band design that is as well graded as possible and still meets criteria. This usually provides the most desirable filter characteristics. However, in some cases, a more uniform or more steeply graded filter band may be preferable. This usually occurs when it is desirable to obtain more readily available standard gradations or where it is desirable to use onsite materials for economy.

For this example, a standard, readily available gradation, ASTM C33 fine concrete aggregate meets the design band. A designer should specify a filter with the following allowable filter gradation and the specifications may state that ASTM C33 fine concrete aggregate, falls within the specified limits of the filter band. From the design band, using commonly specified sieve sizes, the specification table 26B-11 could be prepared.

Example 26B-5 Category-2 soil—dispersive—continued

Figure 26B-11 Filter design for category-2 soil—dispersive

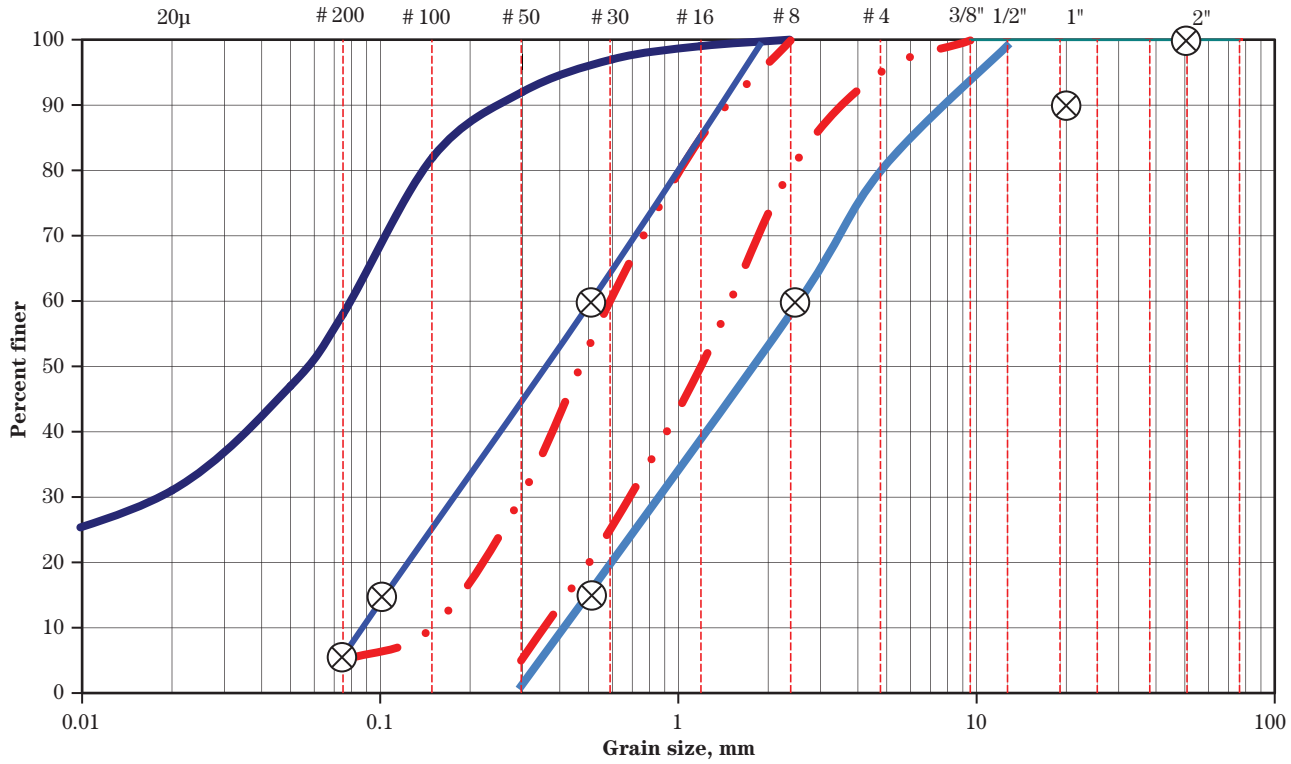


Table 26B-11 Actual allowable filter gradations with category-2 soil—dispersive

Sieve name	Sieve size, mm	% finer
3/8 inch	9.5	100
No. 4	4.76	90-100
No. 8	2.38	65-100
No. 16	1.19	40-90
No. 30	0.59	20-70
No. 50	0.297	10-40
No. 100	0.149	2-15
No. 200	0.075	< 5

Example 26B-6 Category-2 soil after regrading of GSD—nondispersive

Step 1 Plot the gradation curves, table 26B-12 GSD of the base soil materials. Determine if the base soils have dispersive clay content (fig. 26B-12).

In this design example, the soil is given to have a PI of 8 and the fines are not dispersive.

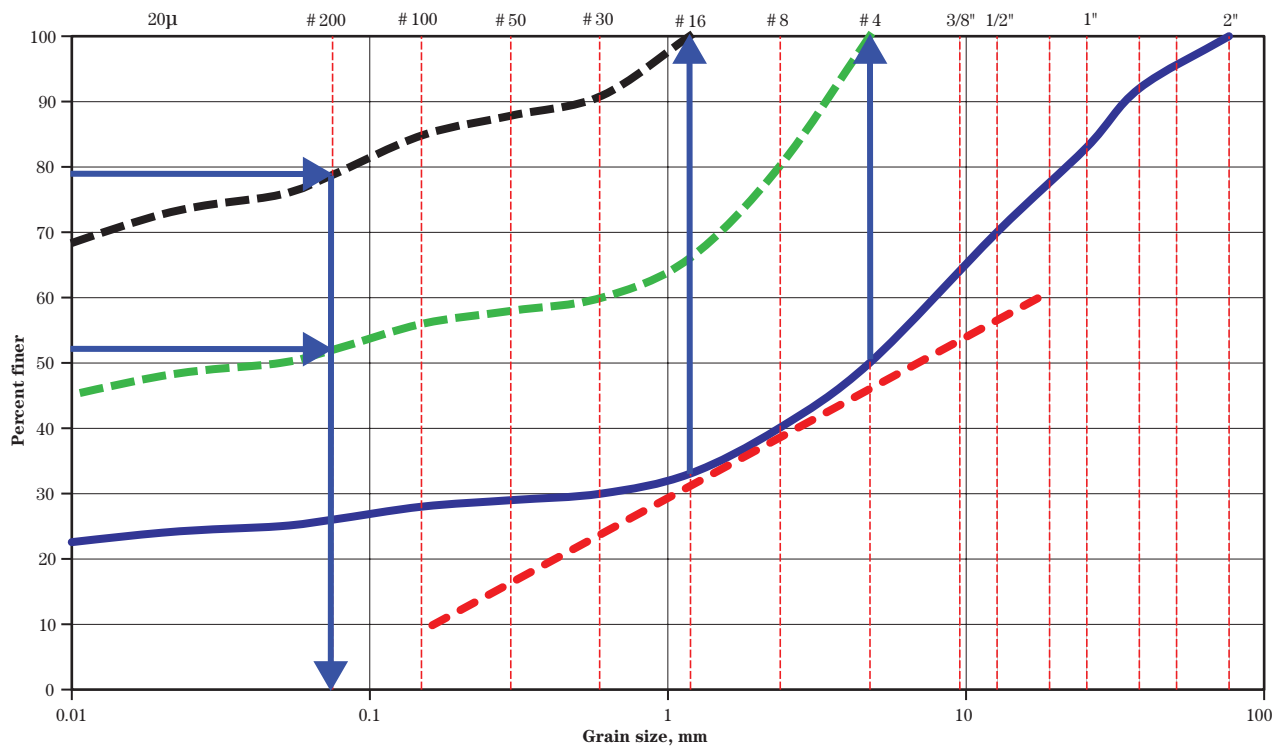
Step 2 Determine if the base soils have particles larger than the No. 4 sieve. At the same time, determine if the base soils are gap graded and potentially subject to internal instability.

- If the base soil has no gravel particles, proceed to step 4.
- If a base soil contains any particles larger than the No. 4 sieve, the soil should be regraded on the No. 4 sieve (go to step 3). By inspection, the

Table 26B-12 GSD curve for sandy silt base soil

Sieve	Size	% finer
3 inches	76.2	100
1-1/2 inches	38.1	92
1 inches	25.4	83
1/2 inch	12.7	70
No. 4	4.75	50
No. 8	2.36	40
No. 16	1.18	33
No. 30	0.6	30
No. 50	0.3	29
No. 100	0.15	28
No. 200	0.075	26
0.05	0.05	25
0.02	0.02	24
0.005	0.005	21

Figure 26B-12 Category-2 soil with regraded GSD—nondispersive



Example 26B-6 Category-2 soil after regrading of GSD—nondispersive—continued

base soil has 50 percent gravel particle content, so regrading on the No. 4 curve is definitely required. However, the gradation curve also has a strong inflection point where the curve becomes flatter than a line with a slope of 20 percent. Consider the effect of regrading the sample at this inflection point, as well. If the soil is regraded on the No. 4 sieve, the percentage of fines will be equal to 52 percent ($26 \div 50 \times 100 = 52\%$). If the soil is regraded on the No. 16 sieve, where the curve inflects to a flat slope, the percentage of fines on the regraded curve is 79 percent ($26 \div 33 \times 100 = 79\%$). In this instance, it really makes no difference to the filter design because for either regraded curve, the soil falls into category 2.

Step 3 Regraded curves are shown in figure 26B-12 for both regrading on the No. 4 sieve and for the No. 16 sieve.

Step 4 Place the base soil in category 2 based on the percent passing the No. 200 (0.075 mm) sieve of the regraded sample. For this example, whether the sample was regraded on the No. 4 sieve or on the No. 16 sieve does not affect the category of the soil. The soil has 52 percent finer than the No. 200 sieve if regraded on the No. 4 sieve and 79 percent fines if regraded on the No. 16 sieve.

Step 5 To satisfy filtration requirements, determine the maximum allowable D_{15} size for the filter. The table uses the d_{85} of the base soil after the sample is regraded.

The criteria table shows that for category-2 soils with clay fines that are not dispersive, the criterion for the maximum D_{15} is maximum $D_{15} \leq 0.7$ millimeter.

Step 6 Establish the minimum D_{15} of the filter as the greater of:

- 0.1 mm, or
- a fifth of the maximum D_{15} size established in step 5

Compute a fifth of the maximum D_{15} size ($0.7 \div 5 = 0.14$ mm). Use 0.14 millimeter as the minimum D_{15} size.

Step 7 Establish the minimum and maximum D_{60} sizes for the design filter band. This rationale is based on a maximum acceptable CU value of 6 and a band width of 5. The minimum D_{60} size is equal to the maximum D_{15} (0.7 mm) size established in step 7. The maximum D_{60} size is then five times the minimum D_{60} ($5 \times 0.7 = 3.5$ mm) size. Locate on a plot and label these two additional control points.

Step 8 Determine the minimum D_5 and maximum D_{100} sizes of the filter in accordance with the criteria table. Label these control points. The maximum particle size is 2 inches and the maximum percentage passing the No. 200 sieve is 5 percent.

Step 9 To ensure that the filter cannot easily segregate during construction, the filter must not be overly broad in gradation. The relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. Calculate a preliminary minimum D_{10} size by dividing the minimum D_{15} size by 1.2.

The minimum D_{15} size is 0.14 millimeter, so the minimum D_{10} size is less than 0.12 millimeter. According to the criteria table, the maximum D_{90} size for filters with a D_{10} size less than 0.5 millimeter is 20 millimeters. Ensure that the resulting design band does not exceed this point.

Step 10 Connect the fine control points to form a partial design for the fine side of the filter band. Connect the coarse control points to form a design for the coarse side of the filter band. Complete the design of the filter band by extrapolating the coarse and fine curves to the 100 percent finer value. The completed design band with the important control points shown is in figure 26B-14. For purposes of writing specifications, select appropriate sieves and corresponding percent finer values

Example 26B-6 Category-2 soil after regrading of GSD—nondispersive—continued

that best reconstruct the design band and tabulate the values.

Additional design considerations

Note that these steps provide a filter band design that is as well graded as possible and still meets criteria. This usually provides the most desirable filter characteristics. However, in some cases, a more uniform or more steeply graded filter band may be preferable. This usually occurs when it is desirable to obtain more readily available standard gradations or where it is desirable to use onsite materials for economy.

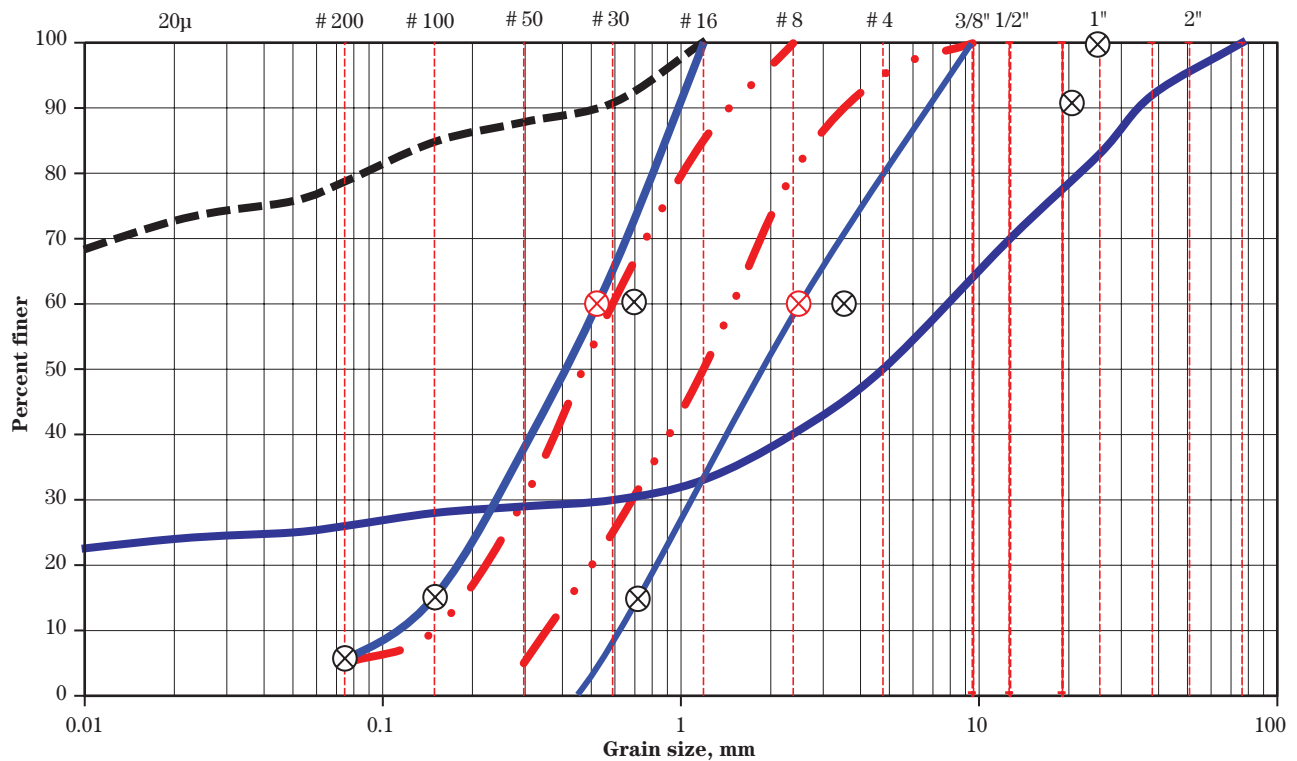
For this example, a standard, readily available gradation, ASTM C33 fine concrete aggregate does not plot within the initial design band. An alternative design is to shift the minimum and maximum D60 sizes to the fine side to incorporate ASTM C33 within the design band.

Table 26B-13

Specification using commonly specified sieve sizes for fine concrete aggregate

Sieve name	Sieve size, mm	% finer
3/8 inch	9.52	90–100
No. 4	4.76	70–100
No. 8	2.38	50–90
No. 16	1.19	30–75
No. 30	0.59	15–55
No. 50	0.297	5–35
No. 100	0.149	≤ 15
No. 200	0.075	≤ 5

Figure 26B-13 Filter design of regraded curve category-2 soil—nondispersive



Example 26B-6 Category-2 soil after regrading of GSD—nondispersive—continued

Check the coefficient of uniformity of the shifted design by computing a new D_{60}/D_{10} ratio for the fine side of the band. The new D_{60} value is 0.45 and the new D_{10} size for the fine side is 0.12, so the new CU value is 3.8 ($0.45 \div 0.12 = 3.8$). This is greater than two, so it is acceptable. A designer could merely specify that the filter supplied meet the requirements of ASTM C33 fine concrete aggregate, or a table with the actual allow-able filter gradations on it could be prepared. From the design band, using commonly specified sieve sizes, table 26B-13 could be prepared. Figure 26B-13 is the filter design after adjusting design band to include ASTM C33 fine aggregate within the design.

Example 26B-7 Category-3 soil with stable GSD and nondispersive fines

Step 1 Plot the gradation curve(s) table 26B-14, GSD of the base soil material(s) (fig. 26B-14). Determine if the base soils have dispersive clay content.

It is given that crumb tests show the fines in the base soil are nondispersive.

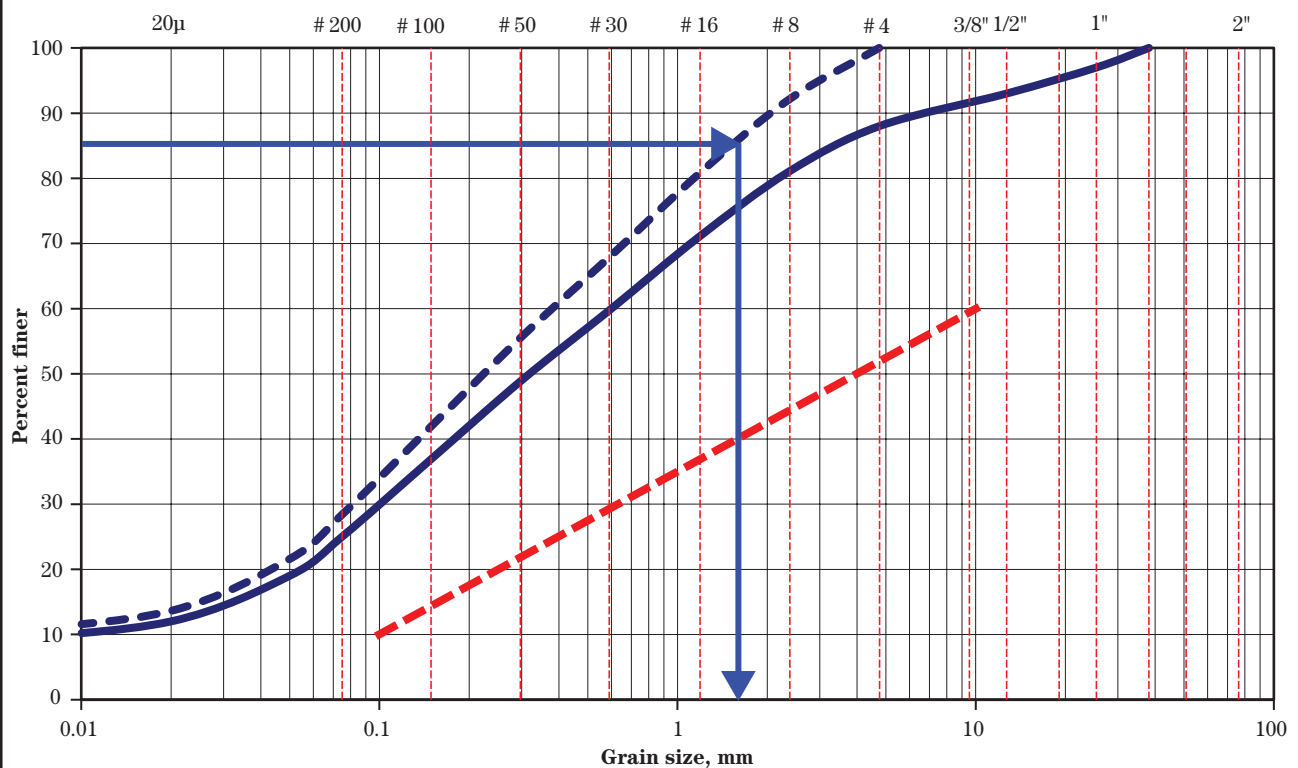
Step 2 Determine if the base soil(s) have particles larger than the No. 4 sieve. At the same time, determine if the base soil(s) are gap-graded and potentially subject to internal instability.

- If the base soil has no gravel particles, proceed to step 4.
- If a base soil contains any particles larger than the No. 4 sieve, the soil should be regraded on the No. 4 sieve (go to step 3).

Table 26B-14 Category 3 soil with stable GSD

Sieve name	Sieve size, mm	% finer
1.5 inches	37.5	100
1 inch	25.4	97
1/2 inch	12.7	93
No. 4	4.75	88
No. 8	2.36	81
No. 16	1.18	71
No. 30	0.6	60
No. 50	0.3	49
No. 100	0.15	37
No. 200	0.075	25
0.05 mm	0.05	19
0.02 mm	0.2	12
0.005 mm	0.005	9

Figure 26B-14 Category-3 soil with stable GSD—nondispersive



Example 26B-7 Category-3 soil with stable GSD and nondispersive fines—continued

Step 3 In step 3, the original gradation curve is regraded on the No. 4 sieve. A correction factor is equal to 100 divided by the percent passing No. 4 sieve, which is 88, so the correction factor is 1.136 ($100 \div 88 = 1.136$). Obtain a regraded curve by multiplying each percent finer from the original curve by 1.136 and plot the adjusted curve as shown in figure 26B-15.

Step 4 Place the base soil in category 3 based on the percent passing the No. 200 (0.075 mm) sieve from the regraded curve at 28.4 percent being between 15 and 40 percent.

Step 5 To satisfy filtration requirements, determine the maximum allowable D_{15} size for the filter.

The criteria table 26B-14 shows that for category-3 soils, the criterion for the maximum D_{15} for the case of nondispersive fines is:

$$\leq \left[\frac{40 - A}{40 - 15} \right] \left[(4 \times d_{85}) - 0.7 \text{ mm} \right] + 0.7 \text{ mm}$$

Read from the regraded curve a d_{85} size of 1.6 millimeter.

$$\leq \left[\frac{40 - 27}{40 - 15} \right] \left[(4 \times 1.6) - 0.7 \text{ mm} \right] + 0.7 \text{ mm} = 3.4 \text{ mm}$$

$$\text{maximum } d_{15} \leq 3.4 \text{ mm}$$

Step 6 Establish the minimum D_{15} of the filter as the greater of:

- 0.1 mm, or
- a fifth of the maximum D_{15} size established in step 5

Compute a fifth of the maximum D_{15} size using the formula and the result is 0.7 mm ($3.4 \div 5 = 0.7$ mm). Use 0.7 millimeter as the minimum D_{15} size.

Step 7 Based on a CU value of 6 and a band width of 5, the minimum D_{60} size is equal to the maximum D_{15} size established in step 6, which is 3.4 millimeters. The maximum D_{60} size is then five times the minimum D_{60} size ($5 \times 3.4 = 17$ mm).

Locate on a plot and label these two additional control points.

Step 8 Determine the minimum D_5 and maximum D_{100} sizes of the filter in accordance with the criteria table. Label these control points. The maximum particle size is 2 inches, and the maximum percentage passing the No. 200 sieve is 5 percent.

Step 9 To ensure that the filter cannot easily segregate during construction, the filter must not be overly broad in gradation. The relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. Calculate a preliminary minimum D_{10} size by dividing the minimum D_{15} size by 1.2.

The minimum D_{15} size is 0.7 millimeter, so the minimum D_{10} size is estimated to be about 0.58 millimeter ($0.7 \div 1.2 = 0.58$ mm). From the criterion table, the maximum D_{90} size is then 25 millimeter. Ensure that the resulting design band does not exceed this point.

Step 10 Connect the fine control points to form a partial design for the fine side of the filter band. Connect the coarse control points to form a design for the coarse side of the filter band. Complete the design of the filter band by extrapolating the coarse and fine curves to the 100 percent finer value. Figure 26B-15 shows the completed design band with the important control points shown as well. For purposes of writing specifications, select appropriate sieves and corresponding percent finer values that best reconstruct the design band and tabulate the values.

Additional design considerations

For this example, the designed filter is not met with readily available standard gradations and, even if the band were adjusted to a more steep shape would not, so no further adjustments are justifiable.

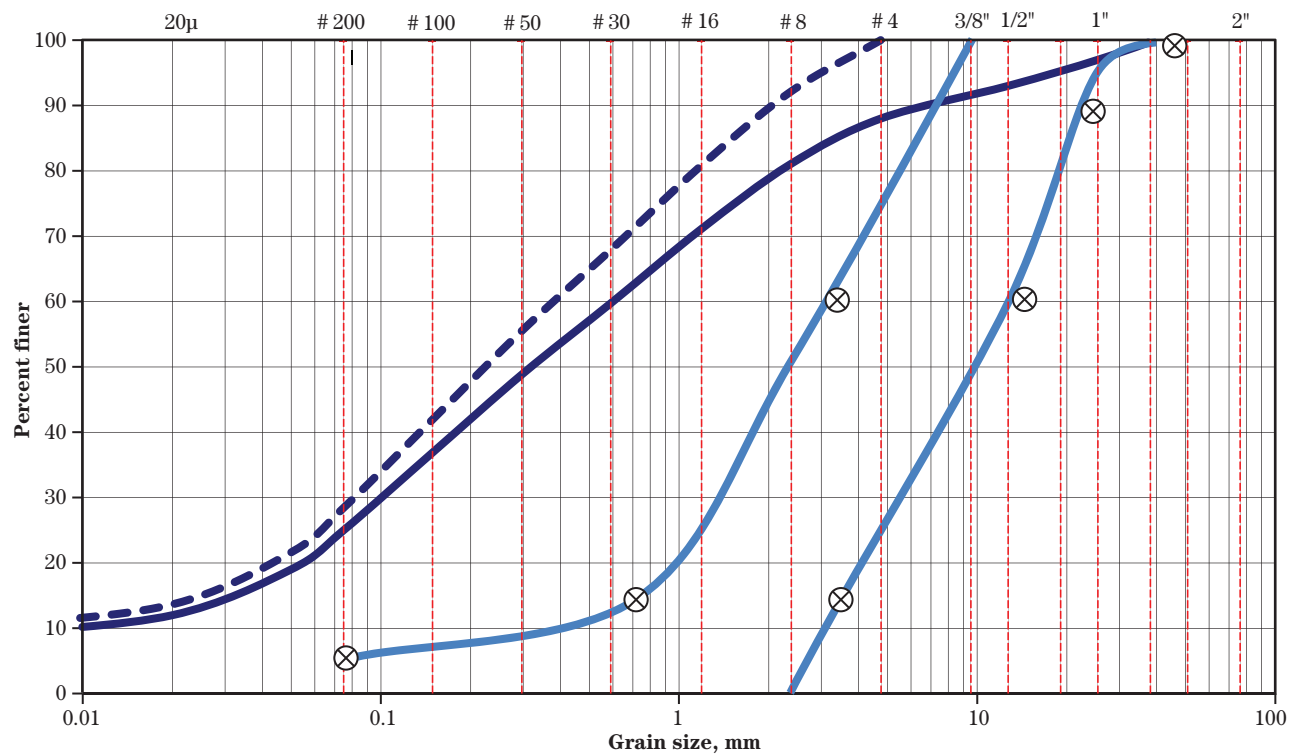
A designer should specify a filter with the following allowable filter gradation. From the design band, using commonly specified sieve sizes, table 26B-15 could be prepared.

Example 26B-7 Category-3 soil with stable GSD and nondispersive fines—continued

Table 26B-15 Specification table with specified sieve sizes for category-3 soil with stable GSD

Sieve name	Sieve size, mm	% finer
1.5 inches	37.5	100
1 inch	25.4	90–100
3/4 inch	19.0	80–100
3/8 inch	9.5	55–95
No. 4	4.76	25–75
No. 8	2.38	10–45
No. 16	1.19	0–25
No. 30	0.59	≤10
No. 50	0.297	≤5

Figure 26B-15 Design filter for category-3 soil with stable GSD—nondispersive fines



Example 26B-8 Category-3 soil with design adjustment

Step 1 Plot the gradation curves, table 26B-16 GSD of the base soil materials (fig. 26B-16). Determine if the base soils have dispersive clay content. It is given that crumb tests show the fines in the base soil are nondispersive.

Step 2 Determine if the base soils have particles larger than the No. 4 sieve. At the same time, determine if the base soils are gap-graded and potentially subject to internal instability.

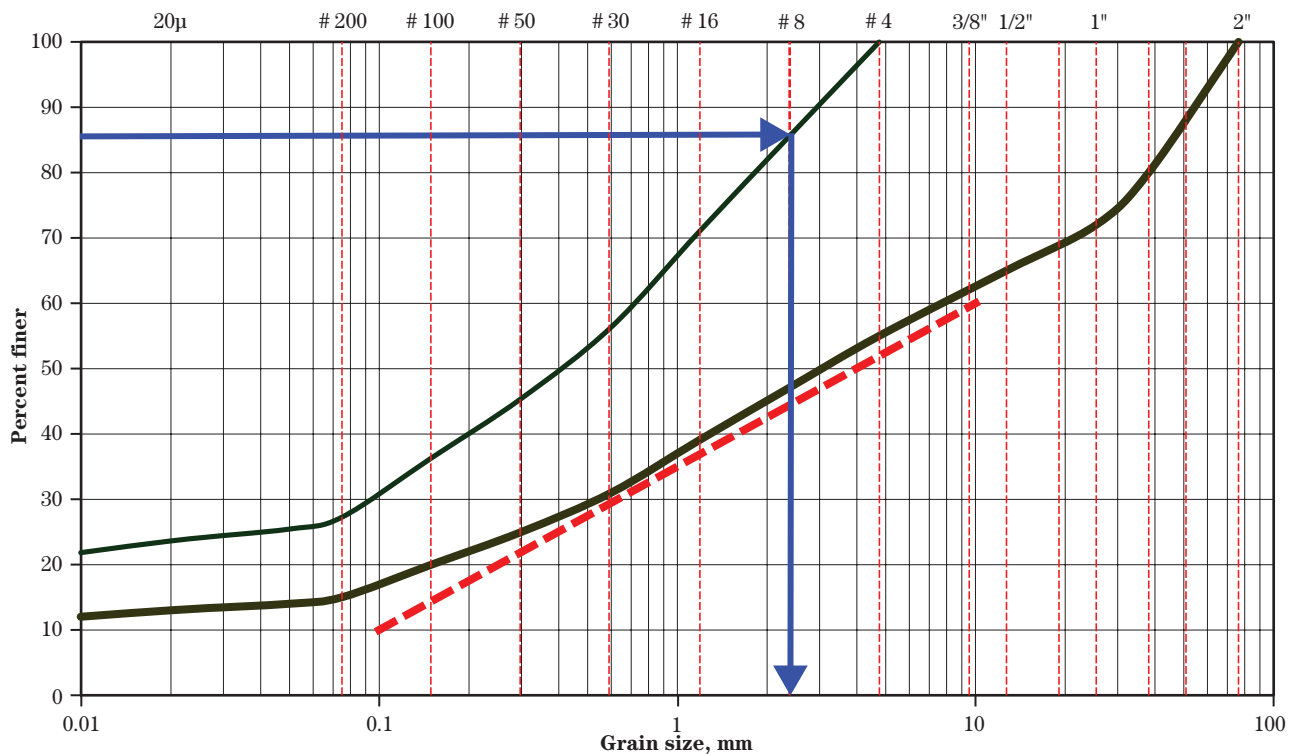
- If the base soil has no gravel particles, proceed to step 4.
- If a base soil contains any particles larger than the No. 4 sieve, the soil should be regraded on the No. 4 sieve (go to step 3), with the following exceptions.

Step 3 Because the soil has gravel content the sample should be regraded on the No. 4 sieve. A correction factor is equal 100 divided by the

Table 26B-16 Gradation for category-3 soils with design adjustments

Sieve	Size mm	% finer	Regraded
No. 4	4.75	55	100
No. 8	2.36	47	86
No. 16	1.18	39	71
No. 30	0.6	31	56
No. 50	0.3	25	46
No. 100	0.15	20	36
No. 200	0.075	15	27
0.05 mm	0.05	14	26
0.02 mm	0.02	13	24
0.005	0.005	11	20

Figure 26B-16 Category-3 soil—nondispersive fines



Example 26B-8 Category-3 soil with design adjustment—continued

percent finer than the No. 4 sieve ($100 \div 53 = 1.89$). Obtain a regraded gradation curve by multiplying each percent finer from the original curve by 1.89 and plot the adjusted curve as shown in figure 26B-16.

Step 4 Place the base soil in category 3 based on the percent passing the No. 200 (0.075 mm) sieve from the regraded curve being between 15 and 39 percent at 27 percent.

Step 5 To satisfy filtration requirements, determine the maximum allowable D_{15} size for the filter.

The criteria table shows that for category-3 soils, the criterion for the maximum D_{15} for the case of nondispersive fines is:

$$\leq \left[\frac{40 - A}{40 - 15} \right] \left[(4 \times d_{85}) - 0.7 \text{ mm} \right] + 0.7 \text{ mm}$$

Read from the regraded curve a d_{85} size of 2.4 mm.

$$\leq \left[\frac{40 - 27}{40 - 15} \right] \left[(4 \times 2.4 - 0.7 \text{ mm}) \right] + 0.7 \text{ mm} = 5.3 \text{ mm}$$

$$\text{Maximum } D_{15} \leq 5.3 \text{ mm}$$

Step 6 Establish the minimum D_{15} of the filter as the greater of:

- 0.1 mm, or
- a fifth the maximum D_{15} size established in step 5

Compute a fifth of the maximum D_{15} size ($5.3 \div 5 = 1.1$ mm). Use 1.1 millimeter as the minimum D_{15} size.

Step 7 Based on a CU value of 6 and a band width of 5, the minimum D_{60} size is equal to the maximum D_{15} size established in step 6. The maximum D_{60} size is then five times the minimum D_{60} size ($5.3 \times 5 = 26.5$ mm). Locate on a plot and label these two additional control points.

Step 8 Determine the minimum D_5 and maximum D_{100} sizes of the filter in accordance with the criteria table. Label these control points. The maximum particle size is 2 inches and the maximum percentage passing the No. 200 sieve is 5 percent.

Step 9 To ensure that the filter cannot easily segregate during construction, the filter must not be overly broad in gradation. The relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. Calculate a preliminary minimum D_{10} size by dividing the minimum D_{15} size by 1.2.

The minimum D_{15} size is 1.1 millimeter, so the minimum D_{10} size is estimated to be about 0.90 millimeter ($1.1 \div 1.2$). From the criterion table, for all soils with a D_{10} size of 0.5 – 1.0 mm, the maximum D_{90} size is then 25 millimeters. Ensure that the resulting design band does not exceed this point.

Step 10 Connect the fine control points to form a partial design for the fine side of the filter band. Connect the coarse control points to form a design for the coarse side of the filter band. Complete the design of the filter band by extrapolating the coarse and fine curves to the 100 percent finer value. The completed design with the important control points is shown in figure 26B-17. For purposes of writing specifications, select appropriate sieves and corresponding percent finer values that best reconstruct the design band and tabulate the values.

Additional design considerations

The maximum D_{60} for the initial control points is too near the maximum D_{90} size that controls the segregation potential of the filter band. The solution to this is to shift the minimum and maximum D_{60} sizes to the fine side. The coefficient of uniformity of the shifted design should be computed to ensure that it is greater than 2 after shifting the points. Compute a new D_{60}/D_{10} ratio for the fine side of the band. The new maximum D_{60} value is about 15, and the new D_{10} size

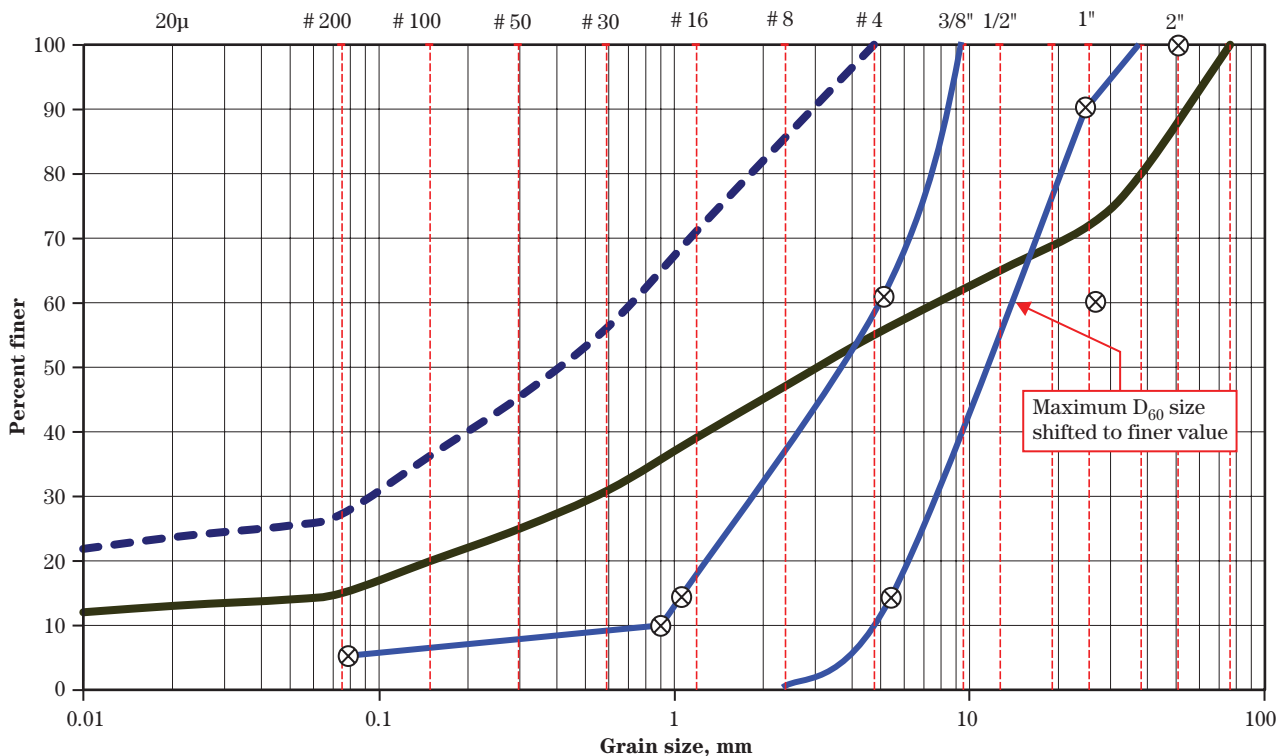
Example 26B-8 Category-3 soil with design adjustment—continued

for the coarse side is 5, so the new CU value is 3.0 (15 ÷ 5.0). This is greater than 2 so is acceptable. Figure 26B-17 shows the adjustment of the maximum D₆₀ size described in this supplemental step. From the design band, using commonly specified sieve sizes, table 26B-17 is prepared.

Table 26B-17 Specification table using commonly specified sieve sizes

Sieve name	Sieve size, mm	% finer
3/8 inch	9.5	100
No. 4	4.76	90–100
No. 8	2.38	70–100
No. 16	1.19	40–100
No. 30	0.59	10–75
No. 50	0.297	0–40
No. 100	0.149	≤ 15
No. 200	0.075	≤ 5

Figure 26B-17 Design filter for category-3 soil



Example 26B-9 Category-4 base soil

Step 1 Plot the gradation curve(s), table 26B-18, GSD of the base soil material(s) (fig. 26B-18). Determine if the base soils have dispersive clay content.

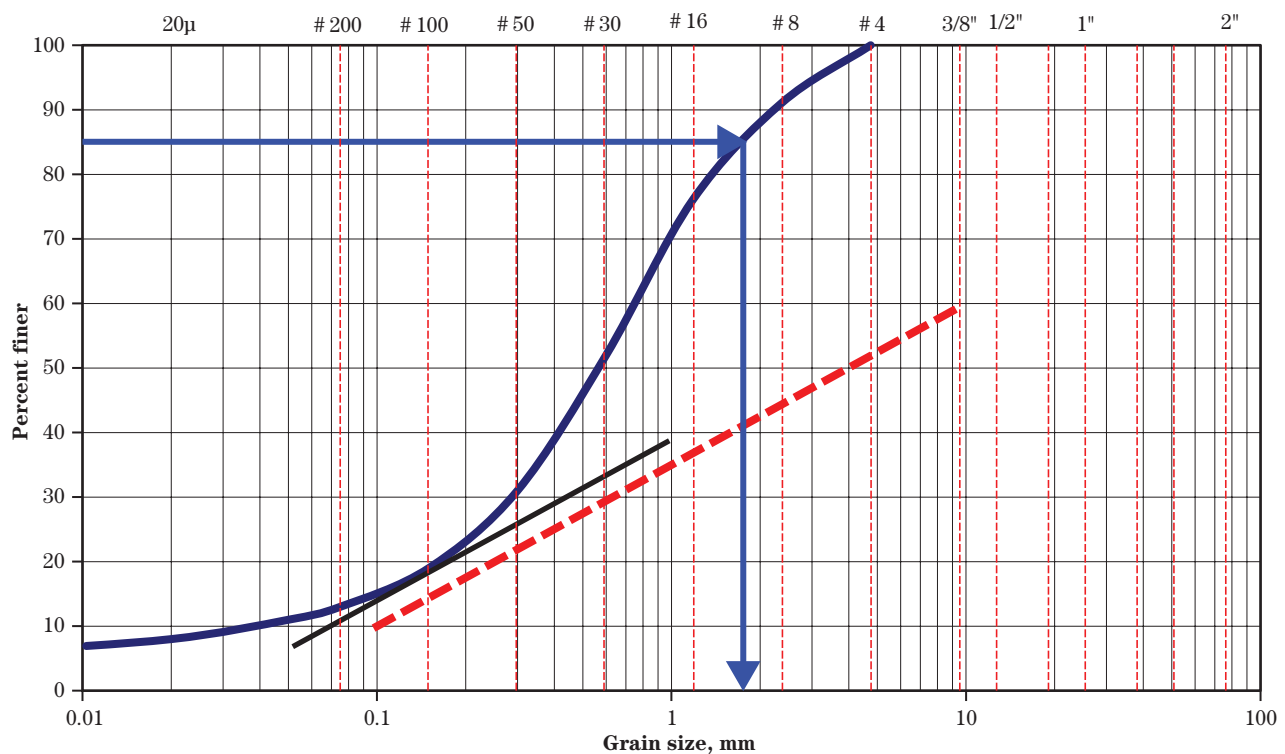
The sample has only 13 percent fines, so whether they are dispersive does not affect the filter design.

Step 2 Determine if the base soil(s) have particles larger than the No. 4 sieve. At the same time, determine if the base soil(s) are gap graded and potentially subject to internal instability.

- If the base soil has no gravel particles, proceed to step 4.
- If a base soil contains any particles larger than the No. 4 sieve, the soil should be regraded on the No. 4 sieve (go to step 3), with the following exceptions.

Table 26B-18 GSD category 4 soil

Sieve	Size mm	% finer
No. 4	4.75	100
No. 8	2.36	91
No. 16	1.18	76
No. 30	0.6	52
No. 50	0.3	31
No. 100	0.15	19
No. 200	0.075	13
0.05 mm	0.05	11
0.02 mm	0.02	8
0.005 mm	0.005	6

Figure 26B-18 Category-4 base soil

Example 26B-9 Category-4 base soil—continued

Step 3 Skip step 3 because the sample does not require grading. No particles are larger than the No. 4 sieve.

Step 4 Place the base soil in category 4 based on the percent passing the No. 200 (0.075 mm) sieve from the GSD curve being less than 15 percent, at 13 percent.

Step 5 To satisfy filtration requirements, determine the maximum allowable D_{15} size for the filter.

The criteria table shows that for category 4 soils, the criterion for the maximum D_{15} is:

$$D_{15} \leq 4 \times d_{85}$$

Read from the PSD curve a d_{85} size of 1.8 millimeters. Then,

$$\text{Max } D_{15} \leq 4 \times d_{85} \leq 4 \times 1.8 \text{ mm} \leq 7.2 \text{ mm}$$

Step 6 Establish the minimum D_{15} of the filter as the greater of:

- 0.1 millimeter
- a fifth of the maximum D_{15} size established in step 5

Compute a fifth of the maximum D_{15} size ($7.2 \div 5 = 1.44$ mm). Use 1.4 millimeters as the minimum D_{15} size.

Step 7 Based on a CU value of 6 and a band width of 5, the minimum D_{60} size is equal to the maximum D_{15} size established in step 6. The maximum D_{60} size is then five times the minimum D_{60} size. For this step, the maximum D_{60} size becomes 36 millimeter (5×7.2). Locate on a plot and label these two additional control points.

Step 8 Determine the minimum D_5 and maximum D_{100} sizes of the filter in accordance with the criteria table. Label these control points. The maximum particle size is 2 inches and the maximum percentage passing the No. 200 sieve is 5 percent.

Step 9 To ensure that the filter cannot easily segregate during construction, the filter must not be overly broad in gradation. The relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. Calculate a preliminary minimum D_{10} size by dividing the minimum D_{15} size by 1.2.

The minimum D_{15} size is 1.4 millimeters, so the minimum D_{10} size is estimated to be about 12 millimeters ($1.4 \div 1.2 = 1.2$ mm). From the criterion table, the maximum D_{90} size is then 30 millimeters. Label this as a control point. At this point, note that the maximum D_{90} size is 30 millimeters, and from step 6, the maximum D_{60} size is 36 millimeters. This indicates that the design band must be steepened to achieve a reasonable filter. Shift the minimum and maximum D_{60} sizes to the fine side to achieve a trial band that is not prone to segregation. The new D_{60} sizes selected are 4 millimeters and 20 millimeters. Check to ensure that the steepened filter does not have a CU value of less than 2. The shifted maximum D_{60} size is 20 millimeters and the D_{10} size is about 6 millimeters, so the CU value is slightly above 3, which is acceptable.

Step 10 Connect the fine control points to form a partial design for the fine side of the filter band. Connect the coarse control points to form a design for the coarse side of the filter band. Complete the design of the filter band by extrapolating the coarse and fine curves to the 100 percent finer value. Figure 26B-19 shows the completed design band with the important control points. For purposes of writing specifications, select appropriate sieves and corresponding percent finer values that best reconstruct the design band and tabulate the values.

Additional design considerations

Note that these steps provide a filter band design that is as well graded as possible and still meets criteria. This usually provides the most desirable filter characteristics. In this case, a more uniform or more steeply graded filter band was required to prevent segregation.

Example 26B-9 Category-4 base soil—continued

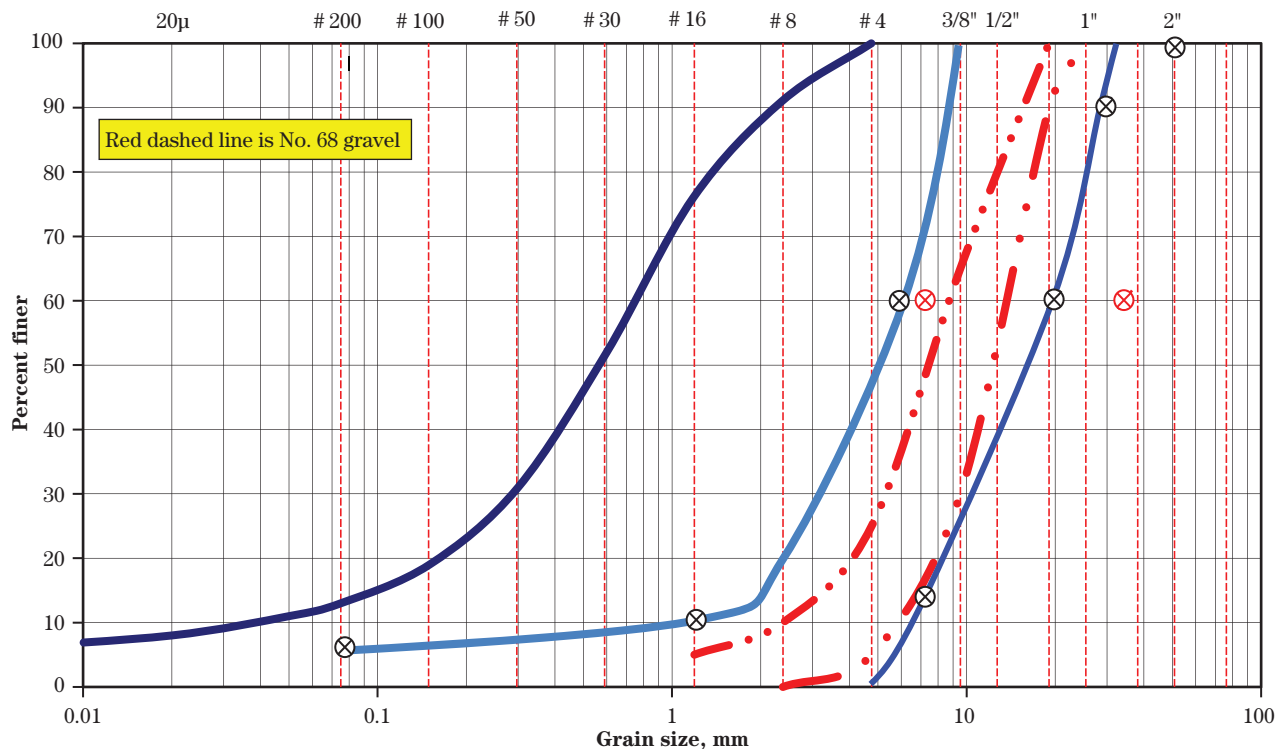
The steeper band also allowed use of a standard gradation, ASTM D448, number 68 gravel, which is plotted as a red dashed line on the solution plot.

A designer should specify a filter with the following allowable filter gradation. From the design band, using commonly specified sieve sizes, the specification table 26B-19 could be prepared.

Table 26B-19 Specification table from the design band using commonly specified sieve sizes

Sieve name	Sieve size, mm	% finer
1.5 inch	37.5	100
1 inch	25.4	80–100
3/4 inch	19.0	60–100
1/2 inch	12.7	40–100
3/8 inch	9.5	25–85
No. 4	4.76	0–50
No. 8	2.38	0–30
No. 16	1.19	≤ 10
No. 30	0.59	≤ 5

Figure 26B-19 Design filter for category-4 base soil



Example 26B-10 Category-4 soil—unstable portions of GSD

Step 1 Plot the gradation curve(s), table 26B-20, GSD of the base soil material(s) (fig. 26B-20). The sample has less than 15 percent fines, so whether they are dispersive does not affect the filter design.

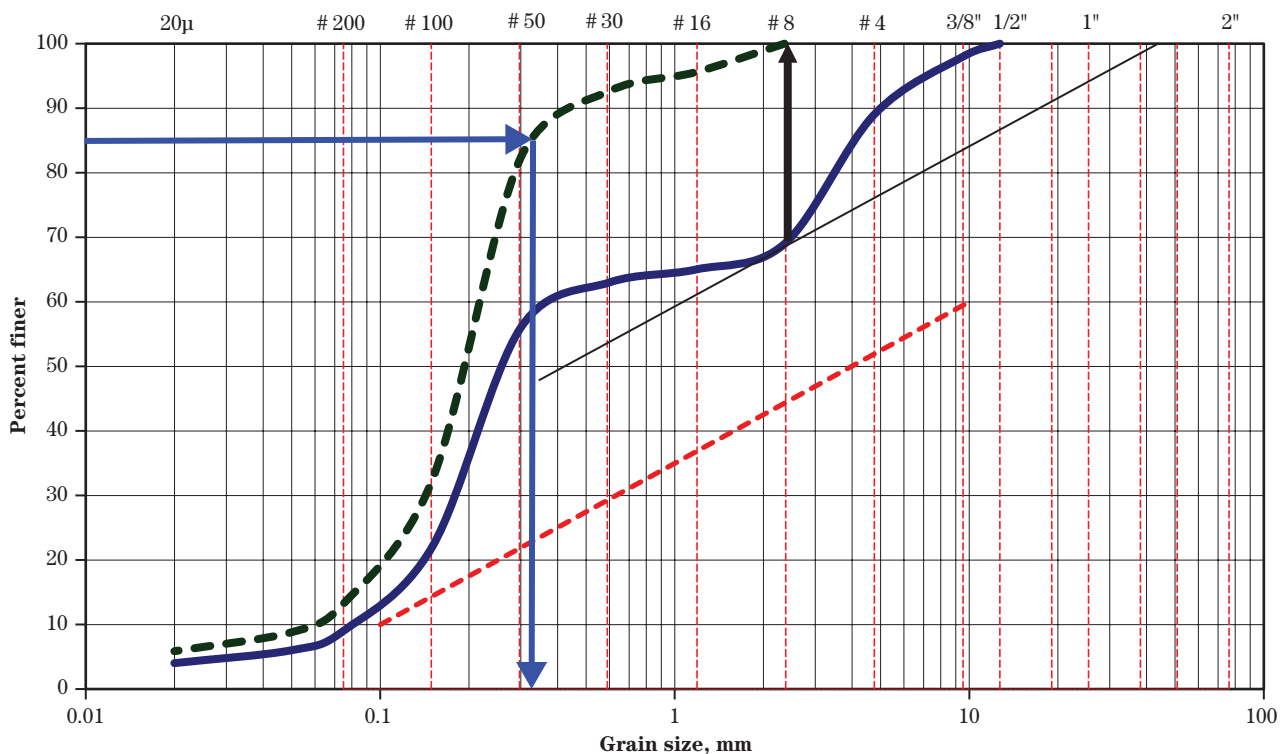
Step 2 Determine if the base soil(s) have particles larger than the No. 4 sieve. At the same time, determine if the base soil(s) are gap-graded and potentially subject to internal instability.

- If the base soil has no gravel particles, proceed to step 4.
- If a base soil contains any particles larger than the No. 4 sieve, the soil should be regraded on the No. 4 sieve (go to step 3), with the following exceptions. By inspection the soil has a gap-graded curve, so additional regrading is necessary.

Table 26B-20 GSD for category-4 soil with unstable portions of GSD

Sieve	Size mm	% finer	Regraded
1/2 inch	12.7	100	
3/8 inch	9.525	98	
No. 4	4.75	89	
No. 8	2.36	49	100
No. 16	1.18	45	92
No. 30	0.6	44	90
No. 50	0.3	40	82
No. 100	0.15	22	45
No. 200	0.075	9	14
0.05 mm	0.05	6	10
0.02 mm	0.02	4	8

Figure 26B-20 Category-4 soil with unstable GSD



Example 26B-10 Category-4 soil—unstable portions of GSD—continued

Step 3 By inspection, an inflection in the gradation curve occurs at about the No. 8 sieve size, with the portion of the curve below this point being flatter than the Sherard curve. Then, the gradation curve should be regraded at this sieve. The percent finer than the No. 8 sieve is 68 percent, so the correction factor is 100 times the percent passing each sieve divided by 68 percent, a correction factor of 1.47. Multiply each sieve percent finer value by this to obtain a regraded curve, which is plotted above. The percent finer on the No. 200 sieve after regrading is 13 percent.

Step 4 Place the base soil in category 4 based on the percent passing the No. 200 (0.075 mm) sieve from the regraded gradation curve being less than 15 percent at 13 percent.

Step 5 To satisfy filtration requirements, determine the maximum allowable D_{15} size for the filter.

The criteria table shows that for category 4 soils, the criterion for the maximum D_{15} for the case of nondispersive fines is:

$$\text{Max } D_{15} \leq 4 \times d_{85}$$

Read from the regraded gradation curve a d_{85} size of 0.32 millimeters.

$$\text{Max } D_{15} \leq 4 \times 0.32 \leq 1.3 \text{ mm}$$

Step 6 Establish the minimum D_{15} of the filter as the greater of:

- 0.1 millimeter, or
- a fifth the maximum D_{15} size established in step 5

Compute a fifth of the maximum D_{15} size which is 26 millimeters ($1.3 \div 5 = 0.26 \text{ mm}$). Use 0.25 millimeter as the minimum D_{15} size.

Step 7 Based on a CU value of 6 and a band width of 5, the minimum D_{60} size is equal to the maximum D_{15} size established in step 6. The maximum D_{60} size is then five times the minimum D_{60} size. For this step, the maximum D_{60} size becomes 6.5 millimeter ($5 \times 1.3 = 6.5 \text{ mm}$). Locate on a plot and label these two additional control points.

Step 8 Determine the minimum D_5 and maximum D_{100} sizes of the filter in accordance with the criteria table. Label these control points. The maximum particle size is 2 inches and the maximum percentage passing the No. 200 sieve is 5 percent.

Step 9 To ensure that the filter cannot easily segregate during construction, the filter must not be overly broad in gradation. The relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. Calculate a preliminary minimum D_{10} size by dividing the minimum D_{15} size by 1.2.

The minimum D_{15} size is 0.25 millimeter. From the criterion table, the maximum D_{90} size for all filters with D_{10} sizes less than 0.5 millimeter is 20 millimeters. Ensure that the resulting design band does not exceed this point.

Step 10 Connect the fine control points to form a partial design for the fine side of the filter band. Connect the coarse control points to form a design for the coarse side of the filter band. Complete the design of the filter band by extrapolating the coarse and fine curves to the 100 percent finer value. Figure 26B-21 shows the completed design band with the important control points. For purposes of writing specifications, select appropriate sieves and corresponding percent finer values that best reconstruct the design band and tabulate the values.

Additional design considerations

Note that these steps provide a filter band design that is as well graded as possible and still meets criteria. For this example, assume that a more narrowly graded filter is sought for one or more reasons. Perhaps a the user wishes to guarantee more uniformity of the product or reduce the potential for variation during the contract. In either case, the design band may be made more poorly graded, or narrowly graded, by shifting the maximum and minimum D_{60} sizes of the design band to finer sizes. For the design example, the D_{60} sizes are shifted to values of 0.6 and 2.5.

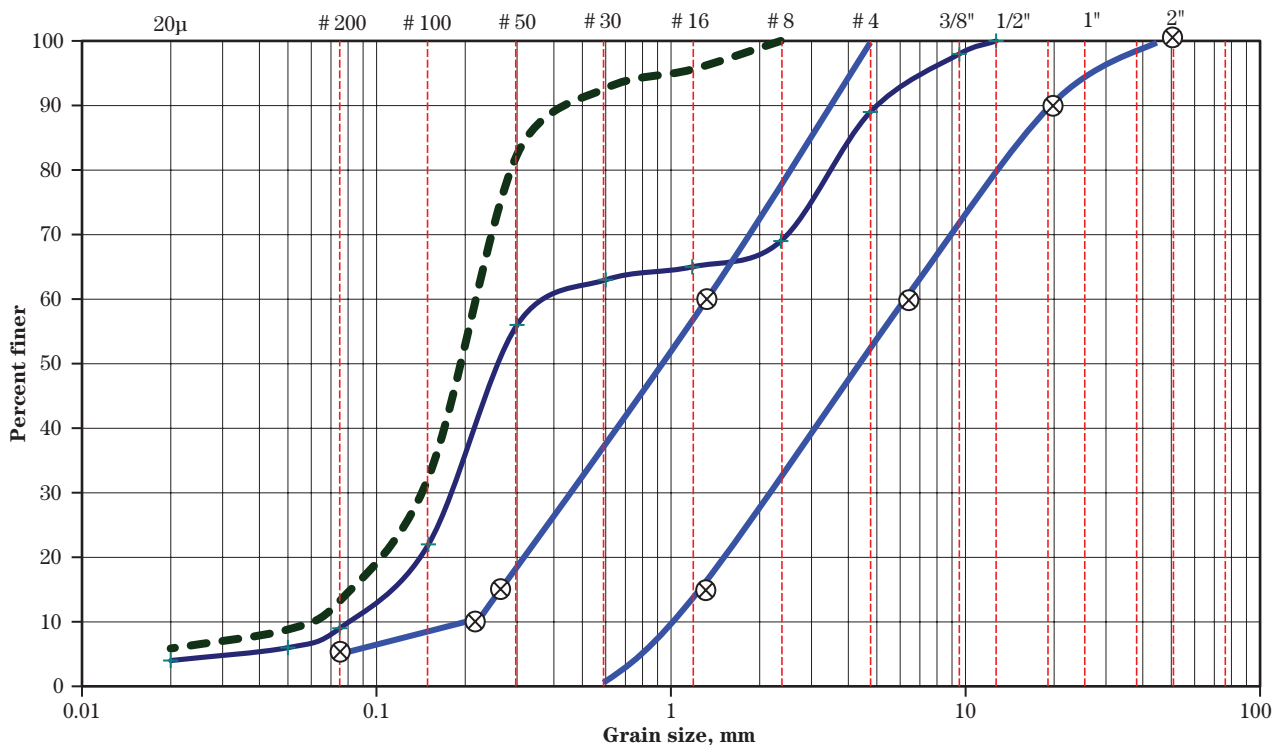
Example 26B-10 Category-4 soil—unstable portions of GSD—continued

This reflects that the alternative filter design has a lower segregation potential, which is logical because it is more narrowly graded than the initial design.

The specifications for the steeper or more narrowly graded filter is shown in the alternative table 26B-22 and is plotted in figure 26B-22.

The filter design for the first alternative design is specified with the following allowable filter gradation. From the design band, using commonly specified sieve sizes, specification table 26B-21 can be prepared.

Figure 26B-21 Design filter category-4 soil with unstable GSD



Example 26B-10 Category-4 soil—unstable portions of GSD—continued

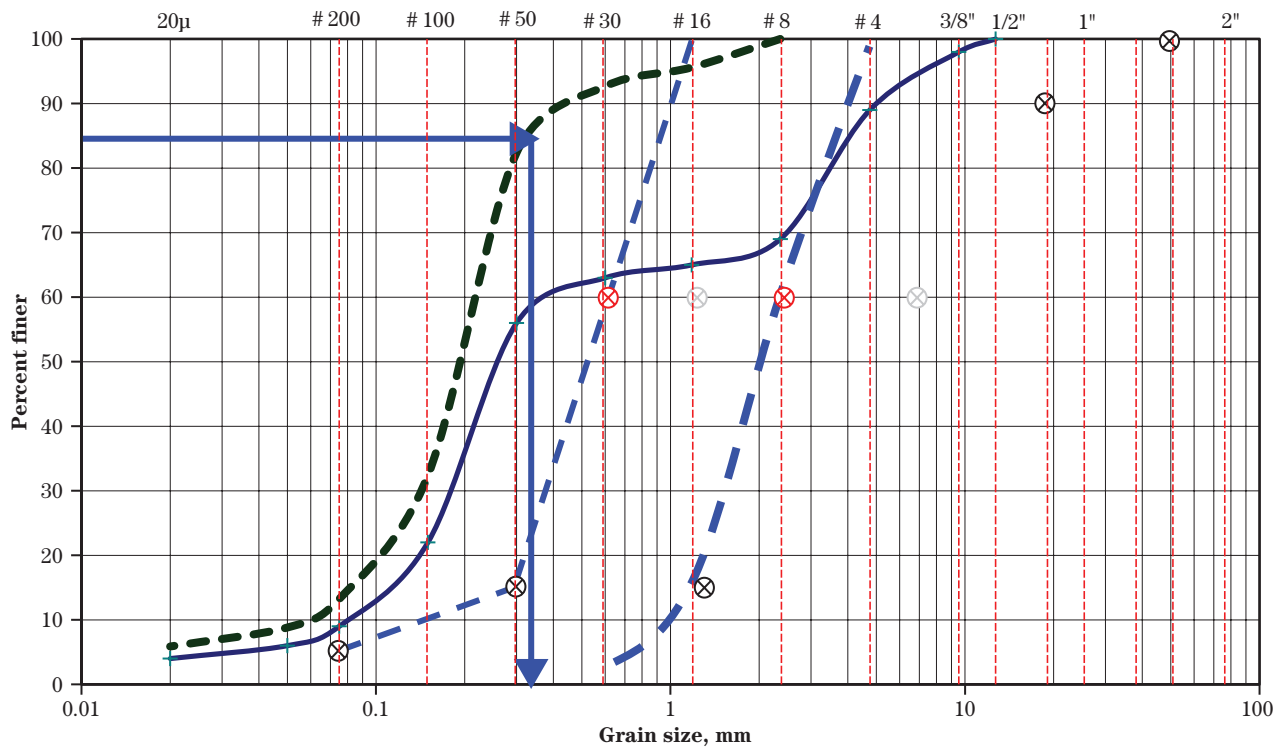
Table 26B-21 Specification table using commonly available sieve sizes

Sieve name	Sieve size, mm	% finer
1 inch	25.4	100
3/4 inch	19.0	90–100
3/8 inch	9.5	70–100
No. 4	4.76	50–100
No. 8	2.38	30–85
No. 16	1.19	15–60
No. 30	0.59	0–30
No. 50	0.297	≤ 10

Table 26B-22 Specification table with allowable filter gradation

Sieve name	Sieve size, mm	% finer
No. 4	4.76	100
No. 8	2.38	60–100
No. 16	1.19	15–100
No. 30	0.59	0–50
No. 50	0.297	0–10
No. 100	0.149	≤ 5

Figure 26B-22 Category-4 soil with unstable GSD alternative design



Example 26B-11 Category-4 soil fine filter—design is for coarse filter compatibility

Step 1 Plot the gradation curve(s) of the base soil material(s) (fig. 26B-23). The base material for this example is a fine filter band that has been designed to filter a category 2 base soil. The designed filter has a maximum D_{15} size of 0.6 mm and a minimum D_{15} size of 0.18. It has a minimum d_{85} size of about 1.2 mm. Note that ASTM C33 fine concrete aggregate plots within the design filter band. This example involves a design for a coarse filter to be compatible with this finest side of the filter band.

Step 2 Determine if the base soil(s) are gap-graded or otherwise potentially subject to internal instability. At the same time, determine if the base soil has particles larger than the No. 4 sieve. The fine side of the filter band will control the design of the coarse filter, and the fine side of the curve does not have particles larger than the No. 4 sieve, so regrading the sample is not required.

Step 3 Skip step 3 because the sample does not require grading. No particles are larger than the No. 4 sieve.

Step 4 Place the base soil in category 4 because the filter designed has less than 15 percent finer than the No. 200 sieve.

Step 5 To satisfy filtration requirements, determine the maximum allowable D_{15} size for the filter.

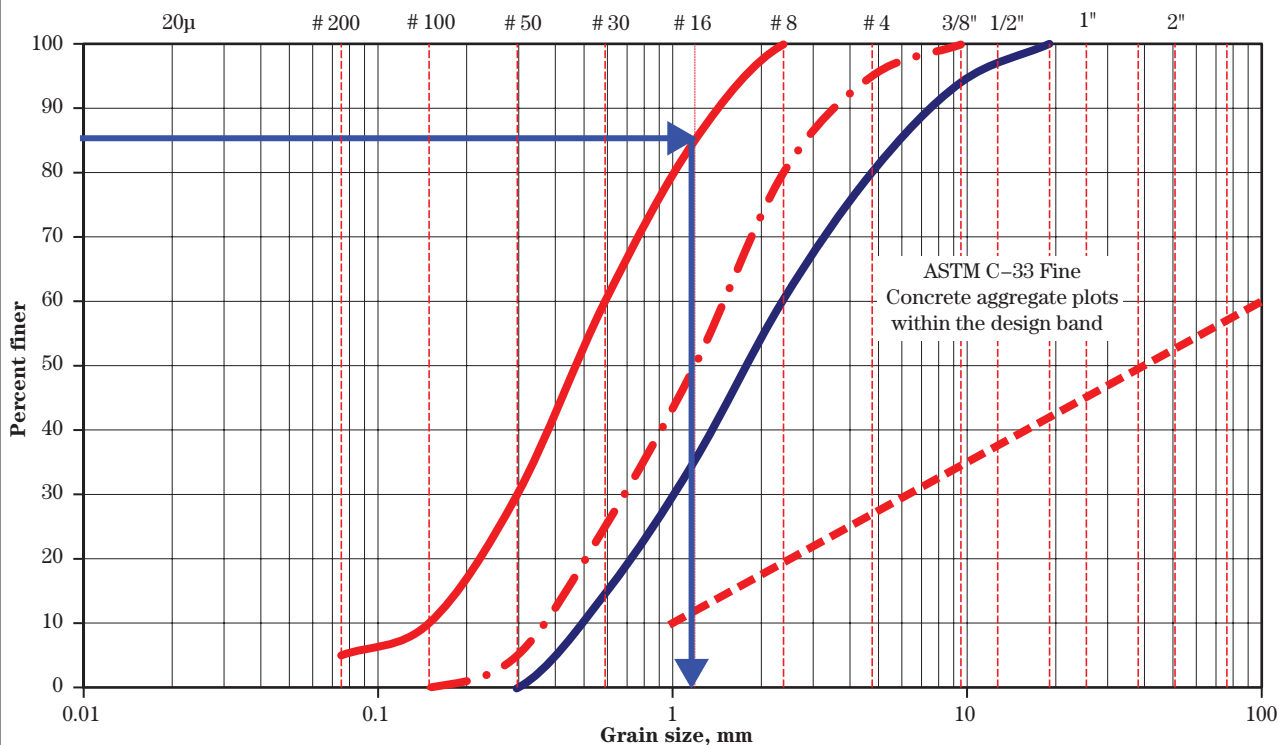
The criteria table shows that for category 4 soils, the criterion for the maximum D_{15} is:

$$\text{Max } D_{15} \leq 4 \times d_{85}$$

Use the fine side of the fine filter band to obtain the minimum d_{85} size of 1.2 mm.

$$\text{Max } D_{15} \leq 4 \times 1.2 \leq 4.8 \text{ mm}$$

Figure 26B-23 Base soil for example 26B-11 is a fine filter design band, shown with a minimum d_{85} size of 1.2 mm



Example 26B-11 Category-4 soil fine filter—design is for coarse filter compatibility—continued

Step 6 Establish the minimum D_{15} of the filter as the greater of:

- 0.1 millimeter, or
- a fifth the maximum D_{15} size established in step 5

Compute a fifth of the maximum D_{15} size ($4.8 \div 5 = 1.0$ mm). Compare the minimum D_{15} size to the d_{15} size of the base soil to determine the filter being designed is sufficiently greater in permeability than the base filter band. The d_{15} size on the coarse side of the base soil filter band is about 0.6 mm, so the ratio of the minimum D_{15} to the base soil's d_{15} is less than 2. Even though it requires a more narrow design band than normal, it is advisable to adjust the minimum D_{15} of the filter being designed to at least a d_{15} size of 2.0 millimeter to achieve a higher permeability. Permeability is proportional to the square of the d_{15} size of sands. If the designed filter has a d_{15} size that about 3.5 times the d_{15} of the base filter, the permeability of the filter being designed should be at least about $(3.5)^2 = 12$ times the permeability of the base filter.

Step 7 Based on a CU value of 6 and a band width of 5, the minimum D_{60} size is equal to the maximum D_{15} size established in step 6, or 4.8 mm. The maximum D_{60} size is then five times the minimum D_{60} size. For this step, the maximum D_{60} size becomes 24.0 millimeters (5×4.8). Locate on a plot and label these two additional control points.

Step 8 Determine the minimum D_5 and maximum D_{100} sizes of the filter in accordance with the criteria table. Label these control points. The maximum particle size is 2 inches, and the maximum percentage passing the No. 200 sieve is 5 percent.

Step 9 To ensure that the filter cannot easily segregate during construction, the filter must not be overly broad in gradation. The relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. Using the value for the minimum D_{15} size selected of 0.2 millimeter, estimate a minimum D_{10} size by dividing by 1.2 to obtain an estimated minimum D_{10} size for the filter being designed of $2.0 \div 1.2 = 1.7$ millimeters.

From the criterion table, the maximum D_{90} size is then 30 mm. Label this as a control point. By examination, the maximum D_{60} size from previous steps is too near the maximum D_{90} size. This indicates that the design band must be steepened to achieve a reasonable filter. Shift the minimum and maximum D_{60} sizes to the fine side to achieve a trial band that is not prone to segregation. The new D_{60} sizes selected are 3.5 millimeters and 18 millimeters. This adjustment is shown in figures 26B-25 and 26B-26.

Step 10 Connect the fine control points to form a partial design for the fine side of the filter band. Connect the coarse control points to form a design for the coarse side of the filter band. Complete the design of the filter band by extrapolating the coarse and fine curves to the 100 percent finer value. The initial design band is shown in figure 26B-24. For purposes of writing specifications, select appropriate sieves and corresponding percent finer values that best reconstruct the design band and tabulate the values.

Table 26B-23 Category-4 soil fine filter—design for coarse filter compatibility

Example 26B-11		
Sieve	Sieve size, mm	% finer
No. 4	4.75	
No. 8	2.36	100
No. 16	1.18	85
No. 30	0.6	60
No. 50	0.3	30
No. 100	0.15	10
No. 200	0.075	4

Additional design considerations

In this case, a more uniform or more steeply graded filter band was required to prevent segregation.

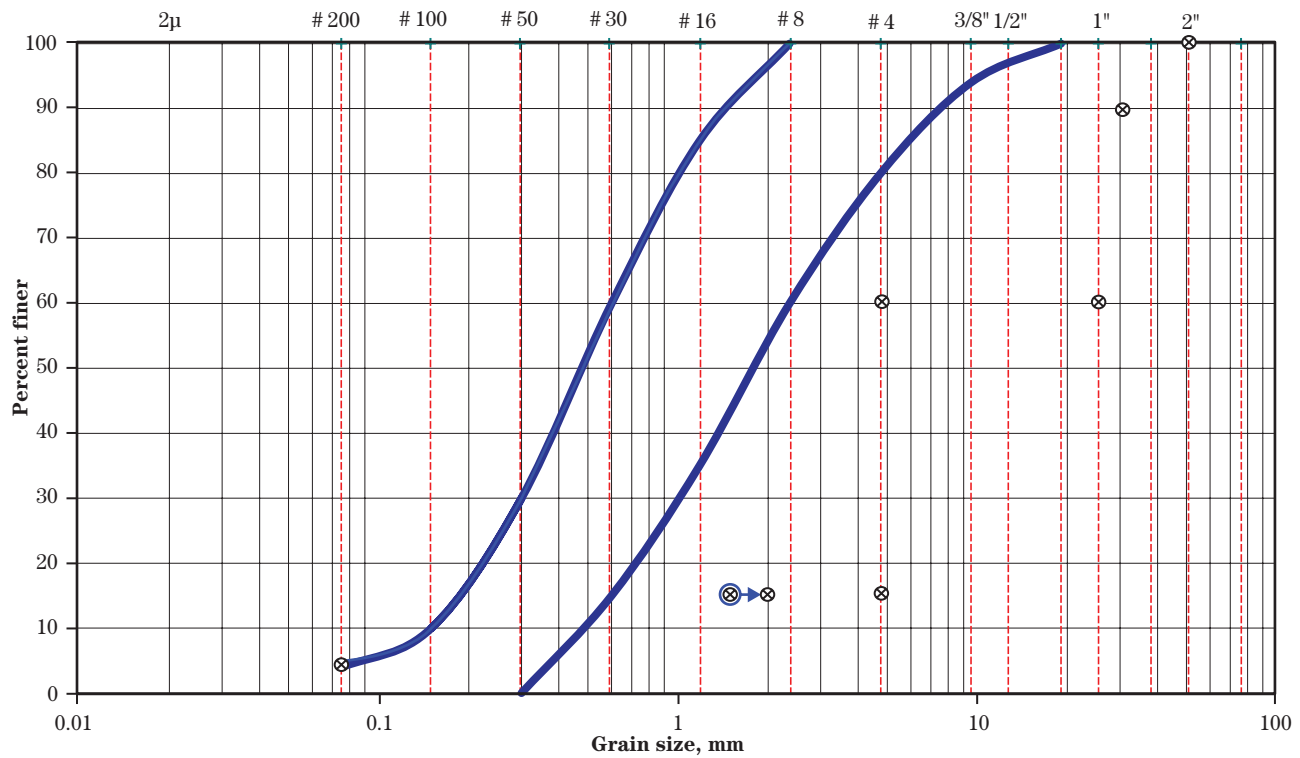
A designer should specify a filter with the following allowable filter gradation. From the design band, using commonly specified sieve sizes, table 26B-24 could be prepared.

Example 26B-11 Category-4 soil fine filter—design is for coarse filter compatibility—continued

Table 26B-24 Specification table for category-4 soil fine filter

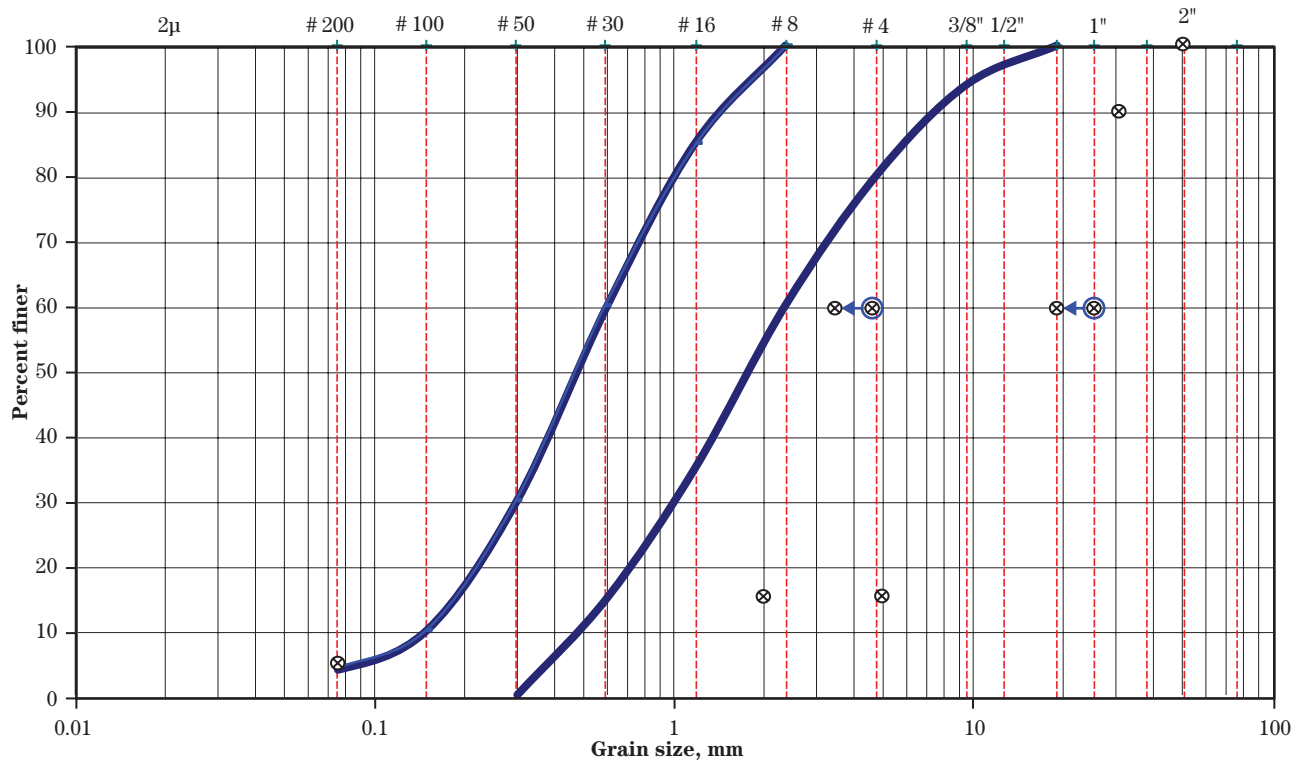
Sieve name	Sieve size, mm	% finer
1 inch	25.4	100
3/4 inch	19.0	90–100
3/8 inch	9.5	60–100
No. 4	4.76	15–70
No. 8	2.38	0–30
No. 16	1.19	≤ 10
No. 30	0.59	≤ 5

Figure 26B-24 Preliminary design adjust D_{15}



Example 26B-11 Category-4 soil fine filter—design is for coarse filter compatibility—continued

Figure 26B-25 Preliminary design adjust D_{60}



Example 26B-11 Category-4 soil fine filter—design is for coarse filter compatibility—continued

Figure 26B-26 Modified to limit segregation showing ASTM C33 sand

