RMC Filter Evaluation (Continuation) Toolbox

RMC Internal Erosion Suite

RMC-CPD-2023-04

January 2024

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Cover Photo: Construction of Seven Oaks Dam in San Bernadino County, California (source unknown).

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14. ABSTRACT
The spreadsheet tools contained in this toolbox assess the particle retention and permeability criteria for filter materials. It includes modern no-erosion filter design criteria, the Foster and Fell (2001) method for filters that do not meet modern filter design criteria, and the Fell et al. (2008) method for "continuing erosion" condition for constricted exits.

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PREVIOUS EDITION IS OBSOLETE

PREPARED

The results, findings, and recommendations provided in this document are technically sound and consistent with current Corps of Engineers practice.

Adam Gohs, Risk Management Center

REVIEWED

This report has been checked and reviewed and is believed to be in accordance with the standards of the profession.

Tim O'Leary, Risk Management Center

APPROVED

Nate Snorteland, Risk Management Center

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDIXES

1. Introduction

The Risk Management Center (RMC) of the U.S. Army Corps of Engineers (USACE) has developed a suite of Microsoft Excel spreadsheets to support risk assessments for dam and levee safety. Each analysis suite is composed of multiple toolboxes (Microsoft Excel workbooks), and each toolbox contains multiple spreadsheet tools or calculation worksheets (Microsoft Excel worksheets). The RMC Filter Evaluation (Continuation) Toolbox is part of the RMC Internal Erosion Suite.

The information from these spreadsheet tools, along with other pertinent information, informs judgment when developing a list of more and less likely factors and estimating probabilities. USACE best practice for estimating probabilities is to use the best available and multiple methods, but all final probabilities are estimated using team elicitation based on the totality and strength of the evidence.

The RMC continuously works to improve the performance of RMC software; report possible bugs directly to the RMC at the address listed below. Ideally, report suspected errors in written form with a description of the problem and the steps that lead to its occurrence. Suggestions for improvement are also welcomed.

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3. General Overview

3.1. Getting Started

Copy or download the toolbox file to the computer. To open the toolbox file, either:

- Find the file on the computer and double-click it. This opens the file in Microsoft Excel.
- Open Microsoft Excel and use the application to open the file: Once Microsoft Excel is open, go to the File menu at the top of the window and select Open.

The toolbox is an Excel binary workbook (.xlsb) that uses macros. You may need to enable the macros, either before opening the file or by clicking “Enable Content” in the yellow Security Warning message bar with a shield icon that appears after the file is opened. The actual message in the message bar will vary depending on the computer’s settings and installed add-ins. Figure 1 displays examples of different wordings that may appear in the message bar.

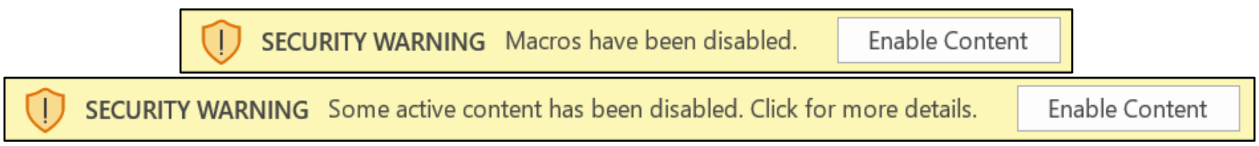


Figure 1. Security warning message bars with the “Enable Content” option to enable macros.

3.2. Organization

Although the toolbox does not provide a calculation cover sheet, adding one is strongly recommended. A calculation cover sheet captures project information, a description and purpose of the calculation, the assumptions for critical input parameters, a summary of the major conclusion and results, and a revision history.

Each toolbox has a similar appearance and organizational structure:

- The first worksheet, About, summarizes the purpose of the toolbox and gives contact information for the RMC software development team.
- The second worksheet, Terms and Conditions, contains the terms and conditions for use of the toolbox (IWR software).
- The third worksheet, Version History, contains the revision history. Semantic versioning is used in the format of MAJOR.MINOR.PATCH:
  - MAJOR – significant worksheet changes not compatible with previous versions.
  - MINOR – additional features or enhancements that do not fundamentally change the calculations.
  - PATCH – backward-compatible bug fixes.

- The fourth worksheet, References, lists the references cited for each calculation worksheet.

The workbook and worksheets are not protected to prevent unwanted changes. However, because the toolbox has user-defined functions (UDFs) and subroutines in Visual Basic, you cannot directly copy worksheets to another workbook without potentially losing functionality. A note in a bold red font at the upper right margin indicates if the selected worksheet includes such features.

At the top of each calculation worksheet, input information for the preparer and checker for quality control (QC) documentation and the calculation title in case multiple copies of the worksheet are created for different analysis scenarios (Figure 2). The footer of each calculation worksheet contains the version number, which can be cross-referenced with the revision history on the third worksheet.

Prepared by:		Office:		Date:	
Checked by:		Office:		Date:	
Calculation Title:					

Figure 2. Calculation worksheet heading.

User-specified input includes values and selections from drop-down lists. User input cells are light yellow, and these cells are unprotected. When cells use drop-down lists, a note in blue font in the right margin of the row alerts the user to use the drop-down list. Conditional formatting applies a gray background to cells that are not based on a user selection. When a user-specified value or calculated value is outside of acceptable ranges, the cell is orange to indicate caution to the user.

All units for user-specified input values are clearly labeled. Most user-specified input values use English units. However, values may be in metric where metric units are more common in practice (e.g., particle size in millimeters or permeability in centimeters per second). The toolbox may convert English units to metric units to perform some calculations or if required for a specific formula based on the reference material for the equation.

If the calculation worksheet is a function of headwater level, up to seven headwater and tailwater levels may be specified at the top of the worksheet. Tailwater may be required to calculate the net hydraulic head and hydraulic gradient. Specify the elevation datum by selecting one of three options from the drop-down list: ft-NAVD88, ft-NGVD29, and Other. The two datum selections include English units of length (feet). If Other is selected, provide a user-specified datum along with feet (e.g., ft-MSL [Mean Sea Level]). Figure 3 through Figure 5 illustrate the three possible scenarios.

Elevation datum		ft-NAVD88		Specify datum				◄ Use drop-down list.
HW (ft)	195.5	201.6	213.5	218.9	223.0	234.0	239.0	◄ Headwater level, HW (ft-NAVD88)
TW (ft)	184.0	184.0	184.0	184.0	184.0	184.0	184.0	◄ Tailwater level, TW (ft-NAVD88)

Figure 3. Headwater and tailwater input: NAVD88.

Elevation datum		ft-NGVD29		Specify datum				◄ Use drop-down list.
HW (ft)	195.5	201.6	213.5	218.9	223.0	234.0	239.0	◄ Headwater level, HW (ft-NGVD29)
TW (ft)	184.0	184.0	184.0	184.0	184.0	184.0	184.0	◄ Tailwater level, TW (ft-NGVD29)

Figure 4. Headwater and tailwater input: NGVD29.

Elevation datum		Other		Specify datum		ft-MSL		◄ Use drop-down list.
HW (ft)	195.5	201.6	213.5	218.9	223.0	234.0	239.0	◄ Headwater level, HW (ft-MSL)
TW (ft)	184.0	184.0	184.0	184.0	184.0	184.0	184.0	◄ Tailwater level, TW (ft-MSL)

Figure 5. Headwater and tailwater input: User-specified datum.

Most calculation worksheets break down complex analysis into computational steps following a logical sequence (Figure 6). Some simpler worksheets do not have steps. Generally, different methodologies are unique worksheets. Some worksheets may include multiple methodologies, which are labeled as options (Figure 7).

Step 1: Select the method of analysis

Figure 6. Example of step banner.

Option 1: Riverside blanket (top stratum) for Cases 5, 7, and 8

Figure 7. Example of option banner.

Some calculation worksheets can perform either a deterministic or probabilistic analysis. Although not required to perform a probabilistic analysis, Palisade @RISK software (standalone version or as part of the Palisade DecisionTools Suite) can customize the probabilistic analysis. A note appears in a bold red font at the upper right-hand margin of a calculation worksheet indicating if this feature is included with the toolbox.

User notes generally appear in the right margin of each calculation worksheet. Some notes are in blue or red font for heightened awareness. These notes include references to source materials for equations, figures, tables, pages, etc. If the RMC modified the source material, the reference citation says “adapted from” instead of “from.”

Tabular and/or graphical summaries are generally the primary output of the toolbox. The UDFs in the PlotScale module change the minimum and maximum values of the x-axis and y-axis for charts. If the calculation worksheet is a function of headwater level, you can define up to five headwater levels of interest and plot them as vertical reference lines. By selecting the chart and then selecting the Filter icon to display the filter pane, you can choose which data series to display. This is useful when computing the results from multiple methodologies, but not all are applicable or desired to display.

4. Background

Once erosion initiates, it continues unless the eroding forces are reduced or migrating eroded particles are impeded. Continuation is the phase of internal erosion where the relationship of the particle-size distribution between the base soil (core) and the filters or adjacent materials controls whether erosion will continue.

Filters are designed to prevent particle movement from intergranular seepage flow where defects are present in a base soil or seepage water flows through pore spaces of a soil mass in an embankment or foundation. A properly designed filter prevents movement of base soils by seepage forces at a discharge face. The filter supports the discharge face such that bridging between closely spaced contact points prevents any movement of base soil particles into the filter. The filter is also sufficiently coarse to allow seepage water to escape freely. Figure 8 illustrates how the filter, in contact with the soil discharge face, supports and prevents soil movement.

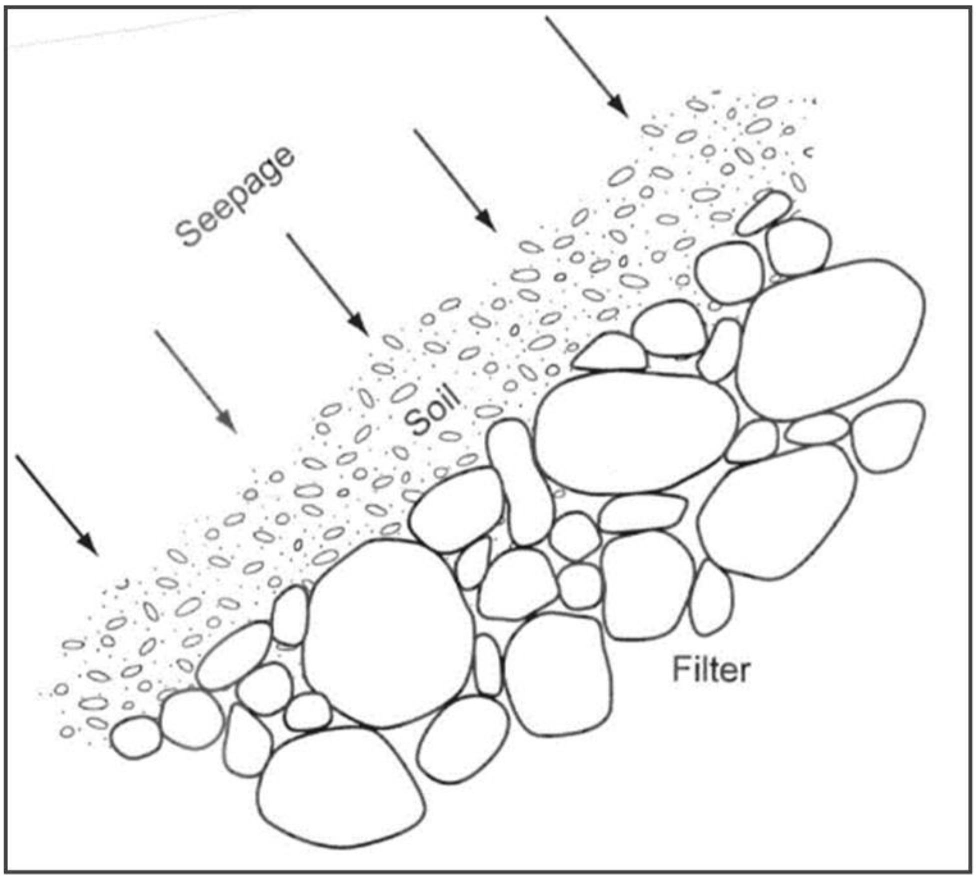


Figure 8. Schematic of filter providing particle retention (FEMA 2011).

The Federal Emergency Management Agency (FEMA) (2011) defines a filter as a soil gradation that meets both particle retention and drainage criteria. The term drain refers to a soil gradation that is typically a second stage to the first-stage filter and conveys larger amounts of seepage. This toolbox assesses the particle retention and permeability criteria of filters to inform the likelihood of continuation of erosion. The procedures for evaluating particle retention can be for single-stage and multi-stage filters.

For multi-stage filters, repeat the procedure for each zone boundary progressing from the finest to the coarsest-grained filter material.

In their published literature, Terzaghi and Sherard used a lowercase "*d*" to represent the particle size (diameter) of the base soil and an uppercase "*D*" for the particle size (diameter) of the filter material. This nomenclature is still commonly used but can be confusing when designing or evaluating two-stage filters since the filter from the first stage becomes the base for the second stage. Therefore, the toolbox uses the following nomenclature:

- $D_{XX}Y$, where D = particle size (diameter)
- XX = percentage passing by weight of particles finer than D
- Y = material designation (either B = base, F = first-stage filter, E = second-stage envelope, or other drainage element).

5. Filter Gradation

This worksheet performs a particle-size analysis of the filter material.

5.1. Filter Gradation

The input includes sieve size (inches or sieve number), particle size (mm) for hydrometer analysis, and percent finer (by weight) for representative coarse and fine gradations of the filter material.

Use the drop-down list to select the sieve size that defines the gradation of the filter material. Coarse sieve designations range from 12 inches to 0.25 inch, and standard sieve designations range from No. 3½ to No. 200. The particle size (*D*) in millimeters is automatically populated if a sieve size is selected. If a hydrometer (sedimentation) analysis was performed on the fine-grained portion of the filter material (i.e., passing the No. 200 sieve), select "Hydrometer" from the drop-down list for sieve size, and input user-specified particle sizes. Particle sizes from sieve or hydrometer analysis must be in descending order.

The user-specified percent finer (by weight) for the filter material gradation (*F*) is the percentage of material passing each sieve size or percentage of particles finer than the diameter given by Stokes' Law for hydrometer analysis. The input must be a decimal number consisting of a whole number and a fractional part (e.g., 100.0 for 100.0 percent passing, 25.5 for 25.5 percent passing). Cells that do not apply or do not require user-specified input have a gray background. Figure 9 is an example of the gradation input.

Sieve Size	D (mm)		F (percent)	
	Sieve	Hydrometer	Coarse	Fine
2-in	50		100.0	100.0
1½-in	37.5		90.0	100.0
1-in	25		70.0	82.0
3/4-in	19		60.0	70.0
1/2-in	12.5		48.0	59.0
3/8-in	9.5		38.0	49.0
No. 4	4.75		25.0	35.0
No. 10	2		18.0	28.0
No. 16	1.18		14.0	24.0
No. 20	0.85		12.0	22.0
No. 30	0.6		9.0	17.0
No. 40	0.425		4.0	13.0
No. 50	0.3		3.0	9.0
No. 70	0.212		1.0	3.0
No. 200	0.075		0.5	1.5
	-			
	-			
	-			
	-			
	-			

Figure 9. Filter Gradation worksheet: Gradation input.

Figure 10 is an example of the summary of the particle-size analysis for the user-specified gradations. The gravel percentage (including coarse and fine gravel percentages), sand percentage (including coarse, medium, and fine sand percentages), fines content (*FC*) (including estimated silt and clay percentages), coefficient of uniformity (C_u) and coefficient of curvature (C_c) for the coarsest and finest filter material are calculated according to the Unified Soil Classification System (American Society of Testing and Materials [ASTM] D2487). An average percentage is also calculated.

The coefficient of uniformity (C_u) is calculated as in Equation 1.

$$C_u = \frac{D_{60}}{D_{10}} \tag{1}$$

where:

D_{10} = particle-size diameter corresponding to 10 percent passing on the cumulative particle-size distribution curve
D_{60} = particle-size diameter corresponding to 60 percent passing on the cumulative particle-size distribution curve

The coefficient of curvature (C_c) is calculated as in Equation 2.

$$C_c = \frac{(D_{30})^2}{D_{10}D_{60}} \tag{2}$$

where:

D_{30} = particle-size diameter corresponding to 30 percent passing on the cumulative particle-size distribution curve

If a gradation does not specify the particle size corresponding to 10 percent passing, 30 percent passing, or 60 percent passing, C_u and C_c are not calculated.

Particle-Size Analysis	Coarse	Fine	Average
Gravel (%): 3-in (75 mm) to 4.75-mm	0.0	0.0	0.0
Coarse Gravel (%): 3-in (75-mm) to ¾-in (19-mm)	0.0	0.0	0.0
Fine Gravel (%): ¾-in (19-mm) to 4.75-mm	0.0	0.0	0.0
Sand (%): 4.75 mm to 0.075 mm	17.0	3.0	10.0
Coarse Sand (%): 4.75-mm to 2.00-mm	0.0	0.0	0.0
Medium Sand (%): 2.00-mm to 0.425-mm	5.0	0.0	2.5
Fine Sand (%): 0.425-mm to 0.075-mm	12.0	3.0	7.5
Fines Content (%): Smaller than 0.075-mm	83.0	97.0	90.0
Silt (%): 0.075-mm to 0.002-mm	83.0	83.0	83.0
Clay (%): Finer than 0.002-mm	0.0	14.0	7.0
Coefficient of uniformity, $C_u = D_{60}/D_{10}$	5.6	-	-
Coefficient of curvature, $C_c = (D_{30})^2 / D_{10} / D_{60}$	0.9	-	-

Figure 10. Filter gradation worksheet: Summary of particle-size analysis.

5.2. Filter Gradation After Segregation or Washout

The filter material may be susceptible to segregation or internal instability. Segregation is the tendency of large particles in a given mass of aggregate to gather together when the material is loaded, transported, or otherwise disturbed.

Segregation can cause pockets of coarse zones that may not be filter-compatible with the material being protected. FEMA (2011) provides filter design guidance to limit segregation potential based on the maximum $D_{90}F$ and the minimum $D_{10}F$. This segregation criteria consider only the design gradation, and the potential for segregation during storing, hauling, dumping, spreading, and compacting must also be considered, which is more subjective and relies on indirect evidence such as construction photographs.

Internal instability describes the loss of soil particles because of seepage. Finer particles in the soil can move within the soil mass under the forces imposed on the particles by seepage flow. Gap-graded or broadly graded soils are examples of internally unstable soils. The RMC Internal Instability Toolbox assesses the susceptibility of the filter material to internal instability. Soils which are susceptible to internal instability are also susceptible to segregation.

Segregation and internal instability result in a coarser filter. Figure 11 illustrates an event tree node that can be added to explicitly consider the likelihood of the filter being segregated or internally unstable during a risk assessment. The particle retention evaluation must consider two gradations of the filter material. Perform the first evaluation using the original or stable gradation and perform the second evaluation using the adjusted gradation after segregation or washout of the erodible finer fraction.

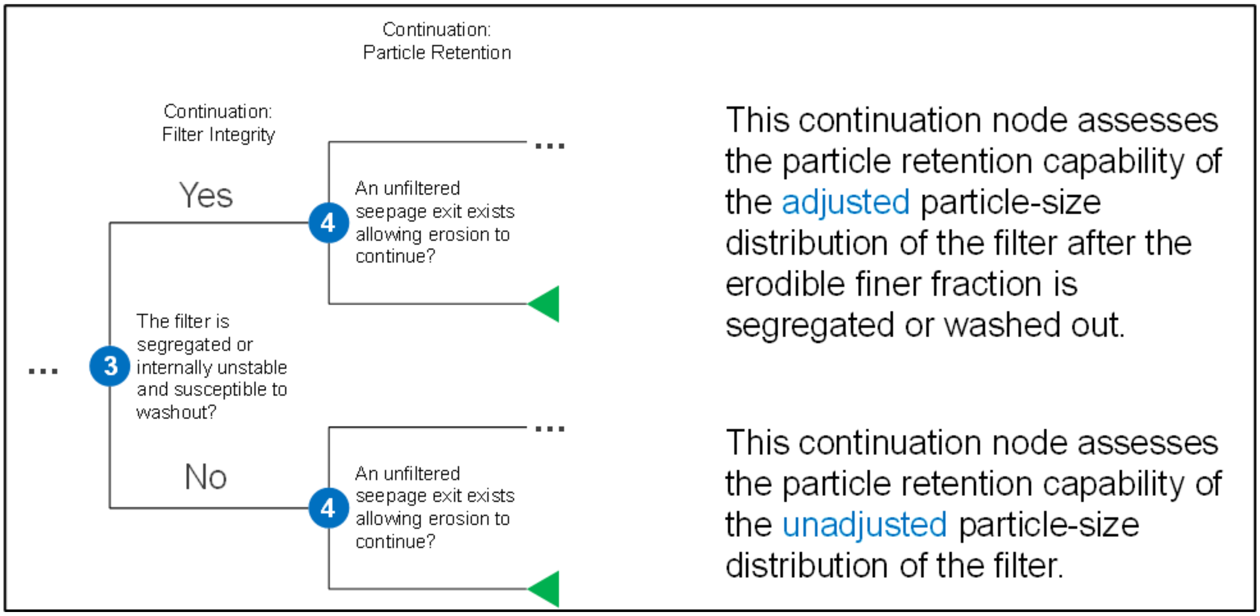


Figure 11. Event tree considerations for segregation or washout of finer fraction.

6. Base Gradation

This worksheet performs a particle-size analysis of the original base soil gradation and, if necessary, the regraded base soil.

6.1. Base Soil Gradation

In step 1, the gradation input and particle-size analysis for the base soil is the same as the filter material detailed.

6.2. Needs Assessment for Regrading

Sherard and Dunnigan (1989) developed the concept of a mathematical adjustment or regrading the base soil to a maximum particle size of 4.75 mm (100 percent passing the No. 4 sieve) for soils with gravels and to correct for broadly graded soils. Broadly graded soils can be internally unstable, where the finer particles can move internally within a matrix of larger particles, and regrading corrects for this phenomenon. Permitting the inclusion of gravel within a base soil gradation leads to a large $D_{85}B$ and subsequently, a large $D_{15}F$. Since gravel particles do not have any particle retention capability in broadly graded soils, the resulting filter gradation is too coarse to provide particle retention of the finer fraction of the base soil.

Step 2 performs a needs assessment for regrading the base soil using a series of questions about various base soil characteristics. Use the drop-down list to assess whether the base soil is gap-graded, because a visual examination of the shape of the gradation curve and judgment are required. Base soils containing particles larger than the No. 4 sieve, having *FC* less than 15 percent, and being broadly graded are evaluated based on the particle-size analysis in step 1. Broadly graded soils are defined by ASTM D2487 as having $1 \leq C_c \leq 3$ and having $C_u \geq 6$ for sands or $C_u \geq 4$ for gravels. The evaluation of broadly graded soils may be inconclusive if C_u and C_c are not calculated because $D_{10}B$ or $D_{30}B$ are not available, for example. For that scenario, manually extrapolate the gradation curve and externally calculate C_u and C_c. Use the drop-down list for the final assessment for whether the base soil is broadly graded. Figure 12 is an example of the responses to the questions about conditions informing regrading.

Step 2: Assess the conditions informing regrading of the base soil

Base Soil Characteristic	Coarse	Fine	
Base soil is gap-graded?	No	No	
Base soil contains particles larger than No. 4 sieve?	No	No	
Base soil has FC < 15%?	No	No	
Base soil is broadly graded per ASTM D2487? For sands: $C_u \geq 6$ and $1 \leq C_c \leq 3$ For gravels: $C_u \geq 4$ and $1 \leq C_c \leq 3$	No	-	
Base soil is broadly graded?	No	No	◄ informed by above

Figure 12. Step 2 of Base Gradation worksheet: Conditions informing regrading.

Based on the responses to the questions, the needs assessment evaluation sequence is as follows:

1. If the base soil is gap-graded, it must be regraded on the particle size (closest sieve) that is missing.

2. If the base soil does not contain particles larger than the No. 4 sieve, regrading is not necessary.

3. If the base soil contains particles larger than the No. 4 sieve, it must be regraded to 100 percent passing the No. 4 sieve, unless it has *FC* less than 15 percent and is not broadly graded.

Figure 13 is an example of the summary of the needs assessment results.

Needs Assessment	Coarse	Fine
Regrade base soil on No. 4 sieve?	No	No
Regrade gap-graded base soil on missing sieve size?	No	No

Figure 13. Step 2 of Base Gradation worksheet: Needs assessment for regrading.

6.3. Base Soil Gradation After Regrading

In step 3, the method of computational regrading is based on the results in step 2. If regrading is not required, “N/A” displays. If the base soil is gap-graded, use the drop-down list to select the sieve size closest to the upper size where the gradation curve has a point of inflection, and the corresponding particle size displays. Cells that do not apply have a gray background. A particle size of 4.75 mm displays if regrading on the No. 4 sieve is required. Figure 14 through Figure 16 illustrate the three possible scenarios.

Step 3: Regrade the base soil, if necessary

Method of Computational Regrading	Coarse	Fine
Missing sieve size for gap-graded soils (i.e., sieve closest to upper size where gradation curve has a point of inflection)		
Maximum particle size for regrading	N/A	N/A

Figure 14. Step 3 of Base Gradation worksheet: No regrading.

Step 3: Regrade the base soil, if necessary

Method of Computational Regrading	Coarse	Fine
Missing sieve size for gap-graded soils (i.e., sieve closest to upper size where gradation curve has a point of inflection)		
Maximum particle size for regrading	4.75	4.75

Figure 15. Step 3 of base gradation worksheet: Regrading on No. 4 sieve.

Step 3: Regrade the base soil, if necessary		
Method of Computational Regrading	Coarse	Fine
Missing sieve size for gap-graded soils (i.e., sieve closest to upper size where gradation curve has a point of inflection)	No. 16	
Maximum particle size for regrading	1.18	N/A

Figure 16. Step 3 of Base Gradation worksheet: Regrading on missing sieve size for gap-graded soils.

If regrading is required, the base soil is regraded to the appropriate maximum particle size. For Regrade the base soil to 100 percent passing the No. 4 sieve, the percentage passing each sieve size of the original base soil is divided by the percentage passing the No. 4 sieve of the original base soil, multiplied by 100 percent, as shown in Figure 17. The procedure for regrading a gap-graded base soil is the same, except to regrade on the particle size that is missing instead of the No. 4 sieve.

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

Figure 17. Example regrading calculation on No. 4 sieve (United States Bureau of Reclamation [USBR] 2011).

Figure 18 is an example gradation of the regraded base soil. If regrading is not required, the gradation from step 1 displays and is used for calculations on subsequent worksheets where gradations after regrading are required input. The summary of the particle-size analysis for the regraded base soil is the same as the filter material, except C_u and C_c are not calculated for the regraded base soil.

Sieve Size	D (mm)		F (percent)	
	Sieve	Hydrometer	Coarse	Fine
No. 4	4.75	-	100.0	100.0
No. 10	2	-	100.0	100.0
No. 16	1.18	-	100.0	100.0
No. 20	0.85	-	100.0	100.0
No. 30	0.6	-	96.0	100.0
No. 40	0.425	-	95.0	100.0
No. 50	0.3	-	94.0	100.0
No. 70	0.212	-	92.0	100.0
No. 100	0.15	-	91.0	100.0
No. 140	0.106	-	86.0	100.0
No. 200	0.075	-	83.0	97.0
Hydrometer	-	0.05	73.0	91.0
Hydrometer	-	0.01	20.0	35.0
Hydrometer	-	0.009	18.0	33.0
Hydrometer	-	0.008	16.0	32.0
Hydrometer	-	0.007	14.0	28.0
Hydrometer	-	0.006	10.0	24.0
Hydrometer	-	0.005	5.0	22.0
Hydrometer	-	0.004	0.0	18.0
Hydrometer	-	0.002	0.0	14.0

Figure 18. Step 3 of Base Gradation worksheet: Regraded base soil gradation.

7. Design for Particle Retention

Modern filter design criteria for particle retention are based on providing a no-erosion condition. The no-erosion condition occurs when a filter material is sufficiently fine to seal with no erosion, or practically no erosion, of the base material. This worksheet assesses the particle retention criterion for no erosion and helps to screen potential failure modes if no erosion is expected. If a filter fails the no-erosion screening, the other erosion boundaries using the Foster and Fell (2001) method described in section 8 are evaluated to assess how much erosion is required for self-filtering to occur and whether it can be tolerated.

7.1. Base Soil Characterization

Step 1 characterizes the base soil. The fines content (*FC*), or percent passing the No. 200 sieve size by weight, of the finest base soil after regrading (if applicable) is obtained from the Base Gradation worksheet, where it is interpolated using a logarithmic scale for particle size and linear scale for percent passing. The base soil category (BSC) is assigned based on the *FC* of the finest base soil after regrading (if applicable). Use the drop-down list to select whether the base soil is non-dispersive or dispersive. Figure 19 is an example of step 1.

Step 1: Assess the gradation of the finest base soil

Finest $D_{85}B$ after regrading (if applicable) 0.042 mm

Fines content of finest base soil after regrading, FC 97.0 percent

Base Soil Category	Fines Content (percent)	Base Soil Description
1	FC > 85	Fine silt and clays
2	40 < FC ≤ 85	Sands, silts, clays, and silty and clayey sands
3	15 < FC ≤ 40	Silty and clayey sands and gravels
4	FC ≤ 15	Sands and gravels

Base soil category, BSC 1

Is base soil dispersive? No

Figure 19. Step 1 of Particle Retention worksheet: Base soil characterization.

7.2. Filter Material Characterization

Step 2 characterizes the filter material. The coarsest $D_{15}F$ is obtained from the Filter Gradation worksheet, where it is interpolated using a logarithmic scale for particle size and linear scale for percent passing. Figure 20 is an example of step 2.

Step 2: Assess the gradation of the coarsest filter material

Coarsest $D_{15}F$ 0.090 mm

Figure 20. Step 2 of Particle Retention worksheet: Filter material characterization.

7.3. Particle Retention Criterion

Sherard et al. (1984) and Foster and Fell (2000) show that the measurable property of the filter that best defines its particle retention capability is the D_{15} of the filter ($D_{15}F$). Research also shows that the correlation between $D_{15}F$ and the d_{85} of the base soil being protected by the filter ($D_{85}B$) provides the best correlation for successful particle retention.

Sherard and Dunnigan (1985) developed the No-Erosion Filter (NEF) test to find the ratio of $D_{15}F$ and $D_{85}B$ that establishes a no-erosion condition for non-dispersive base soils. Additional research by Foster and Fell (2001) at the University of New South Wales (UNSW) helped in developing the no-erosion condition for dispersive base soils. The results of the NEF and UNSW tests were used to develop the modern filter design criteria for particle retention in FEMA (2011).

Step 3 evaluates the no-erosion particle retention criterion by comparing the coarsest $D_{15}F$ to the maximum allowable $D_{15}F$ based on the BSC and knowing whether the base soil is non-dispersive or dispersive. The criteria are a function of $D_{85}B$ and FC, as shown in Figure 21 and Figure 22. If the coarsest $D_{15}F$ is less than or equal to the maximum allowable $D_{15}F$, “Meets” displays next to the calculation. If the criterion is not met, “Fails” displays next to the calculation. A green background displays if the particle retention criterion is met, and an orange background displays if the particle retention criterion is not met.

Based on the particle retention criterion, a statement appears after the calculations indicating if the filter material satisfies the no-erosion particle retention criterion or is too coarse to satisfy the no-erosion particle retention criterion. If the particle retention criterion for no erosion is not met, use the Foster and Fell (2001) method to further evaluate the effectiveness of the filter material for particle retention. Figure 21 and Figure 22 are examples of the two possible scenarios for the no-erosion particle retention criterion.

Step 3: Assess the particle retention (no erosion) criterion

Base Soil Category	Maximum Allowable $D_{15}F$	
	Non-Dispersive Soils	Dispersive Soils
1	$D_{15}F \le 9(D_{85}B)$ but not less than 0.2 mm	$D_{15}F \le 6.5(D_{85}B)$ but not less than 0.2 mm
2	$D_{15}F \le 0.7$ mm	$D_{15}F \le 0.5$ mm
3	$D_{15}F \le (4(D_{85}B) - 0.7)\left(\frac{40 - FC}{25}\right) + 0.7$	$D_{15}F \le (4(D_{85}B) - 0.5)\left(\frac{40 - FC}{25}\right) + 0.5$
4	$D_{15}F \le 4(D_{85}B)$	$D_{15}F \le 4(D_{85}B)$

Maximum allowable $D_{15}F$ 0.379 mm (BSC = 1) Fails

Filter material is too coarse to satisfy the particle retention (no erosion) criterion.
Use the Foster and Fell (2001) methodology to further evaluate the filter material.

Figure 21. Step 3 of Particle Retention worksheet: Particle retention criterion not met.

Step 3: Assess the particle retention (no erosion) criterion

Base Soil Category	Maximum Allowable $D_{15}F$	
	Non-Dispersive Soils	Dispersive Soils
1	$D_{15}F \leq 9(D_{85}B)$ but not less than 0.2 mm	$D_{15}F \leq 6.5(D_{85}B)$ but not less than 0.2 mm
2	$D_{15}F \leq 0.7$ mm	$D_{15}F \leq 0.5$ mm
3	$D_{15}F \leq (4(D_{85}B) - 0.7)\left(\frac{40 - FC}{25}\right) + 0.7$	$D_{15}F \leq (4(D_{85}B) - 0.5)\left(\frac{40 - FC}{25}\right) + 0.5$
4	$D_{15}F \leq 4(D_{85}B)$	$D_{15}F \leq 4(D_{85}B)$

Maximum allowable $D_{15}F$ 0.379 mm (BSC = 1) Meets

Filter material satisfies the particle retention (no erosion) criterion.
Potential failure mode may be excluded from further consideration since erosion will not continue.

Figure 22. Step 3 of Particle Retention worksheet: Particle retention criterion met.

8. Foster and Fell

Many existing embankment dams have filter or transition zones coarser than required by modern filter design criteria. Foster and Fell (2001) indicated that filter materials could be coarser than those resulting from the no-erosion particle retention criterion but still prevent continuous erosion of the base material. For risk assessments of existing embankment dams, it is necessary to evaluate the likelihood of continuation of erosion when such filters are present.

Foster and Fell (2001) developed the continuing erosion filter (CEF) test by modifying the NEF test to evaluate filter performance in terms of how much erosion is required to seal the filter material. The concept of erosion boundaries was developed to describe the filter behavior.

- No-erosion (NE) condition occurs when the filter material seals with no erosion or very little erosion of the base material. The increase in leakage flows is so small that it is likely undetectable. Filters designed and constructed according to modern filter design criteria satisfy the NE condition as described in section 7.

- Some erosion (SE) condition occurs when "some" erosion of the base soil occurs, but the filter quickly seals after particles of the base material clog the surface of the filter.

- Excessive erosion (EE) condition occurs when "excessive" erosion of the base soil occurs, allowing large increases in leakage flow before the filter seals. The extent of erosion is sufficient to damage the embankment.

- Continuing erosion (CE) occurs when the filter is too coarse to allow the eroded base materials to seal the filter, allowing unrestricted or continuous erosion of the base soil and leakage flows.

Figure 23 conceptually shows these erosion boundaries from CEF test behavior.

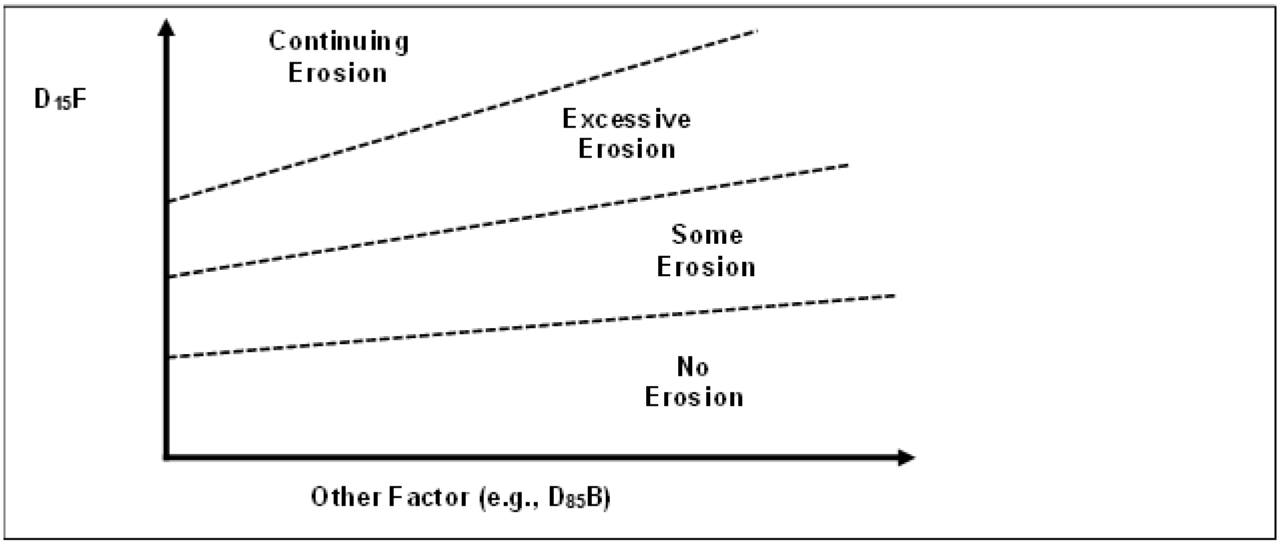


Figure 23. Conceptual erosion boundaries of continuing erosion filter test behavior (adapted from Foster and Fell 2001).

Applying these methods correctly requires understanding the context from which each method was developed, as laboratory test conditions may vary from field conditions. The filter evaluation relies heavily on the research of Foster and Fell (2001) to determine NE, SE, EE, and CE boundaries for the base soil. These erosion conditions were derived from CEF tests, which consisted of a vertically downward flow regime using very high water pressures (i.e., full tap pressure of 300 kPa) and a preformed hole. Therefore, the results are likely conservative.

8.1. Base Soil Characterization

Step 1 characterizes the base soil after regrading (if applicable). Due to the large variability of base soil gradations that may be encountered in practice, gradation test data may include statistical results that are not representative of in situ conditions. FEMA (2011) discusses selecting the representative base soil gradation, and the RMC Soil Classification Toolbox can be used to plot all base soil gradations to help the evaluation. While the range or envelope of base soil gradations are input on the Base Gradation worksheet, use the drop-down list to specify the percentage (*N*) of those gradations considered representative of the base soil gradation for subsequent calculations.

For each input sieve size, the range or envelope of the corresponding percent finer is proportioned to obtain the finer $(100\% - N)/2$ of the base soil gradations and the coarser $(100\% - N)/2$ of the base soil gradations. The average gradation is also obtained for each input sieve size for the range or envelope of the corresponding percent finer. Alternatively, input the representative base soil gradation directly on the Base Gradation worksheet and use a value of 100 percent for *N*, so no further adjustment is made. Fell et al. (2008) recommended selecting representative gradations of the regraded base soil (if applicable), which are indicative of the finer 5 percent of base soil gradations, average gradation, and coarser 5 percent of base soil gradations (i.e., the representative base soil gradation represents N = 90 percent of all gradation tests). Selecting the representative base soil gradation is illustrated in Figure 24.

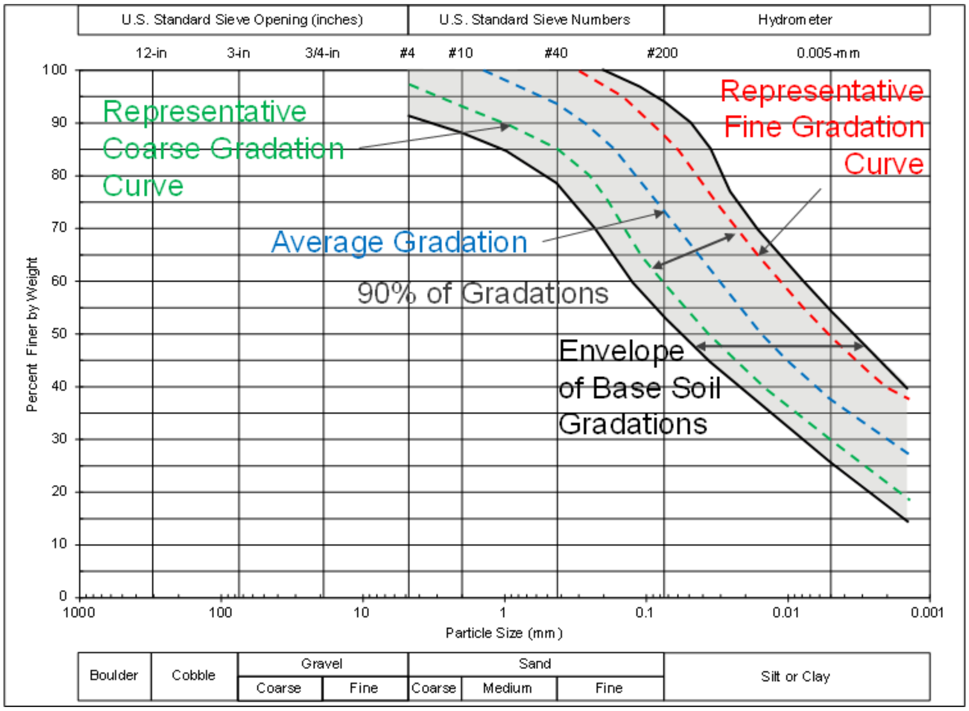


Figure 24. Example of representative gradation curves.

The $D_{95}B$, $D_{90}B$, $D_{85}B$, *FC*, and fine-to-medium sand content (*fm*) of the representative base soil gradation are interpolated using a logarithmic scale for particle size and linear scale for percent passing. For the Foster and Fell (2001) method, the fine-to-medium sand content of the base soil is defined as the percentage between 1.18 mm and 0.075 mm, whereas ASTM D2487 defines fine-to-medium sand as the percentage of soil particles between 2.00 mm and 0.075 mm. Use the drop-down list to select whether the base soil is non-dispersive or dispersive. Figure 25 is an example of step 1.

Step 1: Assess the gradation of the base soil after regrading (if applicable)

Representative base soil gradation, N 80 percent of all gradation tests which is indicative of the coarser 10 percent of the base soil gradations and the finer 10 percent of the base soil gradations

Representative Gradation	$D_{95}B$ (mm)	$D_{90}B$ (mm)	$D_{85}B$ (mm)	FC (%)	fm (%)
Coarse	0.350	0.130	0.080	84.4	15.6
Average	0.140	0.075	0.058	90.0	10.0
Fine	0.072	0.053	0.044	95.6	4.4

where fm = fine-to-medium sand content of the base soil defined as percentage between 1.18 and 0.075 mm

Is base soil dispersive? No

Figure 25. Step 1 of Foster and Fell worksheet: Base soil characterization.

8.2. Filter Material Characterization

Step 2 characterizes the filter material. The range of $D_{95}F$ is obtained from the Filter Gradation worksheet, where it is interpolated using a logarithmic scale for particle size and linear scale for percent passing. Figure 26 is an example of step 2.

Step 2: Assess the gradation of the filter material

Coarsest $D_{15}F$	1.346	mm
Finest $D_{15}F$	0.505	mm

Figure 26. Step 2 of Foster and Fell worksheet: Filter material characterization.

8.3. No-Erosion Boundary

Step 3 evaluates the no-erosion boundary [$(D_{15}F)_{NE}$] for the representative base soil gradations after regrading (if applicable), based on the BSC and whether the base soil is non-dispersive or dispersive. The criteria are the same as the no-erosion criteria on the Particle Retention worksheet and are a function of $D_{85}B$ and *FC* as shown in Figure 27.

Step 3: Assess the no erosion boundary for the representative base soil after regrading

Base Soil Category	Fines Content (percent)	Base Soil Description
1	FC > 85	Fine silt and clays
2	40 < FC ≤ 85	Sands, silts, clays, and silty and clayey sands
3	15 < FC ≤ 40	Silty and clayey sands and gravels
4	FC ≤ 15	Sands and gravels

Base Soil Category	Criteria for No Erosion Boundary	
	Non-Dispersive Soils	Dispersive Soils
1	$D_{15}F \leq 9(D_{85}B)$ but not less than 0.2 mm	$D_{15}F \leq 6.5(D_{85}B)$ but not less than 0.2 mm
2	$D_{15}F \leq 0.7$ mm	$D_{15}F \leq 0.5$ mm
3	$D_{15}F \leq (4(D_{85}B) - 0.7)\left(\frac{40 - FC}{25}\right) + 0.7$	$D_{15}F \leq (4(D_{85}B) - 0.5)\left(\frac{40 - FC}{25}\right) + 0.5$
4	$D_{15}F \leq 4(D_{85}B)$	$D_{15}F \leq 4(D_{85}B)$

Representative Gradation	FC (%)	BSC	$(D_{15}F)_{NE}$ (mm)
Coarse	84.4	2	0.700
Average	90.0	1	0.524
Fine	95.6	1	0.399

Figure 27. Step 3 of Foster and Fell worksheet: No-erosion boundary.

8.4. Continuing Erosion Boundary

Step 4 evaluates the continuing erosion boundary [$(D_{15}F)_{CE}$] from Foster and Fell (2001) for the representative base soil gradations after regrading (if applicable), based on $D_{95}B$ using the criterion shown in Figure 28. If a continuing erosion condition is met for the representative base soil gradation, the other erosion boundary is not assessed.

Step 4: Assess the continuing erosion boundary for the representative base soil after regrading

Criterion for continuing erosion boundary: $D_{15}F > 9(D_{95}B)$ for all soils

Representative Gradation	$(D_{15}F)_{CE}$ (mm)
Coarse	3.152
Average	1.259
Fine	0.650

Figure 28. Step 4 of Foster and Fell worksheet: Continuing erosion boundary.

8.5. Excessive Erosion Boundary

Step 5 evaluates the excessive erosion boundary [$(D_{15}F)_{EE}$] from Foster and Fell (2001) for the representative base soil gradations after regrading (if applicable), based on $D_{95}B$, $D_{90}B$, $D_{85}B$, FC, and fm and whether the base soil is non-dispersive or dispersive, using the criteria shown in Figure 29. The criterion for $D_{95}B$ greater than 2 mm and FC greater than 35 percent was obtained by a curve fit to the

0.25-g/cm^2 contour of erosion loss from CEF tests from Foster and Fell (2001), as recommended by Fell et al. (2008) (see Figure 30).

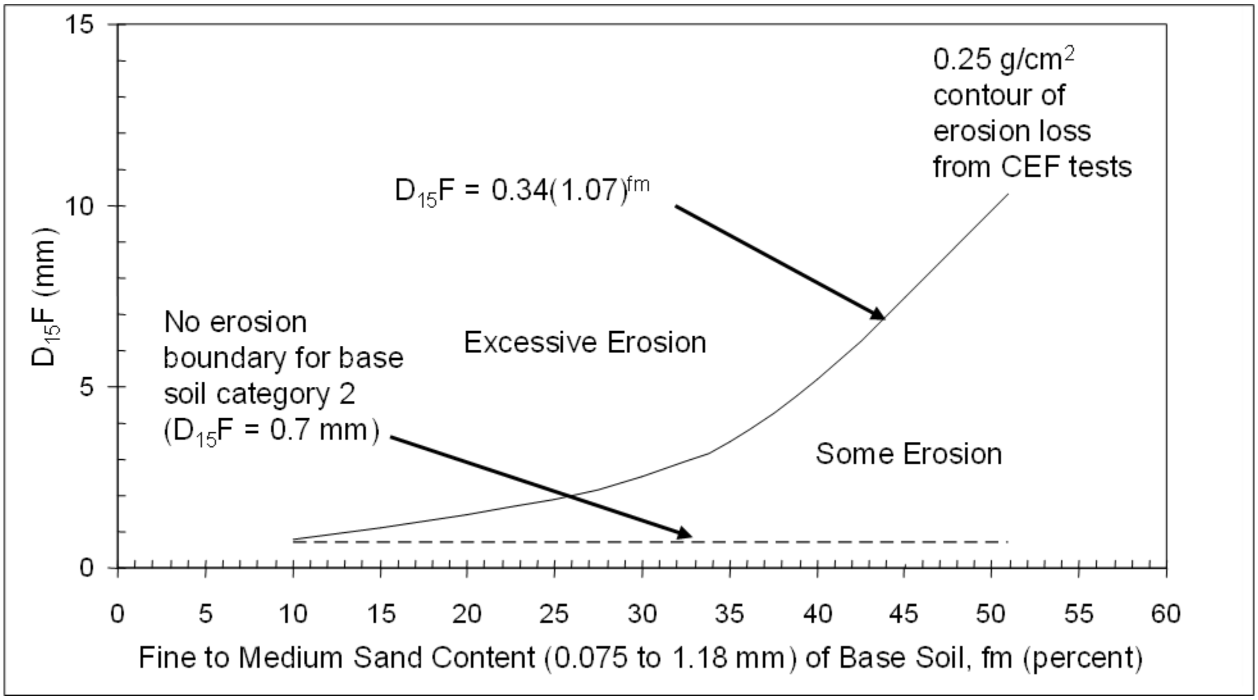


Figure 29. Excessive erosion boundary (adapted from Fell et al. 2008).

Step 5: Assess the excessive erosion boundary for the representative base soil after regrading

Base Soil		Criteria for Excessive Erosion Boundary
A	$D_{95}B \le 0.3$ mm	$D_{15}F > 9(D_{95}B)$
B	0.3 mm $< D_{95}B \le 2$ mm	$D_{15}F > 9(D_{90}B)$
C	$D_{95}B > 2$ mm and FC ≤ 15%	$D_{15}F > 9(D_{85}B)$
D	$D_{95}B > 2$ mm and 15% < FC ≤ 35%	$D_{15}F > 2.5\left((4(D_{85}B) - 0.7)\left(\frac{35 - FC}{20}\right) + 0.7\right)$
E	$D_{95}B > 2$ mm and FC > 35%	$D_{15}F > 0.34(1.07)^{fm}$ (i.e., $D_{15}F$ value for erosion loss of 0.25g/cm^2 in the CEF test)

Representative Gradation	$D_{95}B$ (mm)	FC (%)	Base Soil	$(D_{15}F)_{EE}$ (mm)
Coarse	0.350	84.4	B	1.166
Average	0.140	90.0	A	1.259
Fine	0.072	95.6	A	0.650

Figure 30. Step 4 of Foster and Fell worksheet: Excessive erosion boundary.

8.6. Likelihood of Erosion

Step 6 compares the erosion boundaries for the representative base soil gradation after regrading (if applicable) against the range of $D_{15}F$ (example provided in Figure 31). The ranges of the erosion boundaries for the coarse base soil gradation, average base soil gradation, and fine base soil gradation display as green, blue, and red horizontal lines, respectively. The range for the CE and NE categories extends infinitely beyond their respective boundaries. The erosion boundaries for each representative base soil gradation display as short vertical lines of the same color as the horizontal lines, and the erosion categories are labeled between the boundaries. The range of $D_{15}F$ displays as vertical black lines that intersect these erosion categories.

The proportions of the filter material gradation that fall into the CE, EE, and SE categories are calculated for each of the representative base soil gradations after regrading (if applicable) and are summarized in a table. It is possible for the EE boundary to be the same as the CE boundary. For those scenarios, there is no proportion for EE, and only SE displays. The sum of the proportions must be 100 percent. Fell et al. (2008) recommended estimating the proportions for CE, EE, and SE and then calculating the proportion of the filter material gradation finer than the NE category as in Equations 3, 4, and 5.

$$P_{NE,coarse} = 1 - P_{CE,coarse} - P_{EE,coarse} - P_{SE,coarse} \tag{3}$$

$$P_{NE,average} = 1 - P_{CE,average} - P_{EE,average} - P_{SE,average} \tag{4}$$

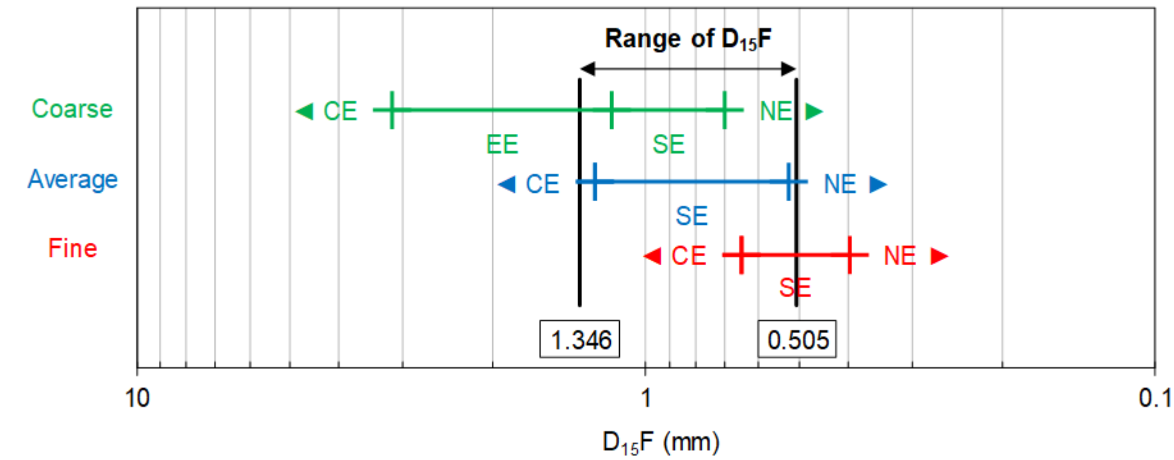
$$P_{NE,fine} = 1 - P_{CE,fine} - P_{EE,fine} - P_{SE,fine} \tag{5}$$

where:

P_{NE} = proportion of the filter material gradation finer than the NE category
P_{SE} = proportion of the filter material gradation for the SE category
P_{EE} = proportion of the filter material gradation for the EE category
P_{CE} = proportion of the filter material gradation coarser than the CE category

Step 6: Estimate the probabilities for each erosion category

Representative Gradation	$(D_{15}F)_{CE}$	$(D_{15}F)_{EE}$	$(D_{15}F)_{NE}$
Coarse	3.152	1.166	0.700
Average	1.259	1.259	0.524
Fine	0.650	0.650	0.399



Representative Gradation	Proportions				Sum
	CE	EE	SE	NE	
Coarse	0%	15%	52%	33%	100%
Average	7%	0%	89%	4%	100%
Fine	74%	0%	26%	0%	100%

Figure 31. Step 6 of Foster and Fell worksheet:
Erosion boundaries for representative base soil gradation.

If the range of $D_{15}F$ does not fall into the CE category (i.e., the gradation of the filter material is finer than the CE boundary), the proportion of the gradation within the CE category is 0 percent. Fell et al. (2008) suggested a procedure to account for the possibility of the gradations being coarser than indicated by the available information, which depends on how much finer the gradations are than the CE boundary. In this procedure, the minimum P_{CE} is based on the ratio of the coarsest $D_{15}F$ to the $(D_{15}F)_{CE}$. Intermediate values are interpolated using a z-variate scale for probability and linear scale for the ratio $D_{15}F/(D_{15}F)_{CE}$ (see Table 1).

Table 1.
Probability of continuing erosion for gradation finer than continuing erosion boundary.

$D_{15}F/(D_{15}F)_{CE}$	0.1	0.2	0.5	1.0
Minimum P_{CE}	0.0001	0.001	0.01	0.1

Use the drop-down list to select the method of analysis as shown in Figure 32. Cells that do not apply if this method is not selected have a gray background.

Estimate P_{CE} by Fell et al. (2008) if filter gradation is finer than CE boundary. Yes

According to Fell et al. (2008), the following table can be used to estimate the probability of continuing erosion if the filter gradation is finer than the CE boundary $(D_{15}F)_{CE}$ to account for the possibility of the gradations being coarser than indicated by the available information using the coarsest $D_{15}F$.

$D_{15}F/(D_{15}F)_{CE}$	0.1	0.2	0.5	1.0
Minimum P_{CE}	0.0001	0.001	0.01	0.1

Representative Gradation	Minimum P_{CE}
Coarse	6.00E-03
Average	#N/A
Fine	#N/A

Figure 32. Step 6 of Foster and Fell worksheet: Estimated probability of continuing erosion.

The probabilities of NE, SE, EE, and CE are estimated by weighting the proportions of NE, SE, EE, and CE for each representative base soil gradation by the percentage of the representative base soil gradation (i.e., the sum of the products of the percentage of each representative base soil gradation and the proportions of NE, SE, EE, and CE for each representative base soil gradation) as shown in Figure 33.

$P_{NE} = ((1 - N/100)/2)(P_{NE,coarse}) + (N/100)(P_{NE,average}) + (1 - N/100)/2)(P_{NE,fine})$	6.33E-02
$P_{SE} = ((1 - N/100)/2)(P_{SE,coarse}) + (N/100)(P_{SE,average}) + ((1 - N/100)/2)(P_{SE,fine})$	7.93E-01
$P_{EE} = ((1 - N/100)/2)(P_{EE,coarse}) + (N/100)(P_{EE,average}) + ((1 - N/100)/2)(P_{EE,fine})$	1.47E-02
$P_{CE} = ((1 - N/100)/2)(P_{CE,coarse}) + (N/100)(P_{CE,average}) + ((1 - N/100)/2)(P_{CE,fine})$	1.29E-01

Note: Probabilities obtained from this method should not be used directly in risk assessments. Rather, the values should be used to help develop a list of more and less likely factors.

Figure 33. Step 6 of Foster and Fell worksheet: Probability of each erosion condition.

9. Summary Plot

This worksheet summarizes the particle retention evaluation on a cumulative particle-size plot showing the filter gradation, base soil gradation after regrading (if applicable), representative base soil gradation after regrading (if applicable), and the NE, EE, and CE boundaries for the coarse, average, and fine representative base soil gradations. There are no user-specified inputs or calculations on this worksheet.

Figure 34 is an example of a Summary Plot worksheet. The solid black lines represent filter gradation, and the dashed black lines represent base soil gradation after regrading (if applicable). The representative coarse base soil gradation, representative average base soil gradation, and representative fine base soil gradation are displayed as green, blue, and solid red lines, respectively. If *N* is equal to 100 percent, the representative coarse and fine base soil gradations overlay the base soil gradation envelope after regrading (if applicable). If *N* is less than 100 percent, the representative coarse and fine base soil gradations plot within the base soil gradation envelope after regrading (if applicable).

The ranges of the erosion boundaries for the coarse base soil gradation and fine base soil gradation are displayed as green and red horizontal lines, respectively. The ranges for the CE and NE categories extend infinitely beyond their respective boundaries. The erosion boundaries for coarse base soil gradation and fine base soil gradation are shown as short vertical lines of the same color as the horizontal lines, and the erosion categories are labeled between the boundaries. The erosion boundaries for the average base soil gradation are shown as short blue vertical lines along the same horizontal axis as the coarse base soil gradation.

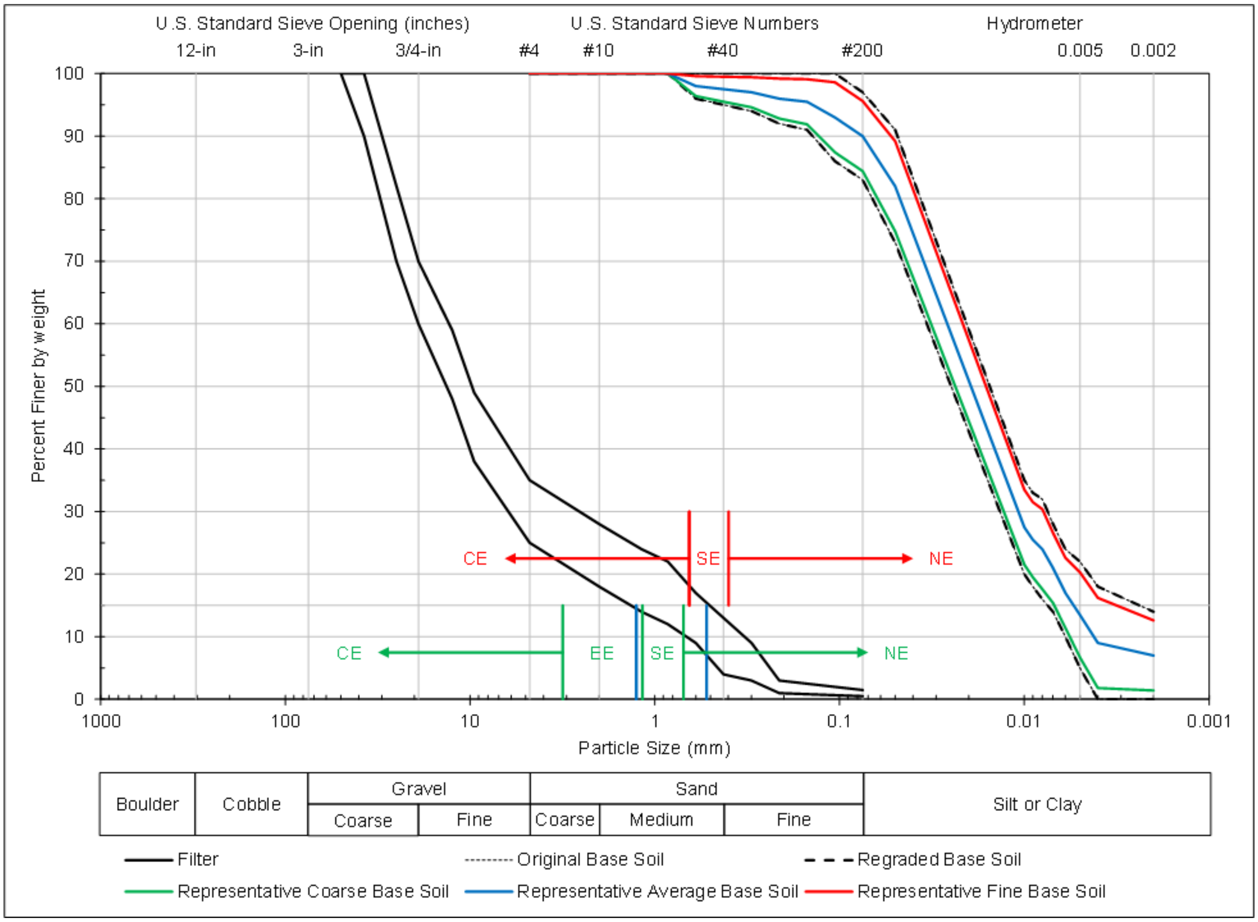


Figure 34. Summary Plot worksheet.

10. Constricted Exit

Constricted, or non-erodible, exits consist of open joints, defects, or cracks in conduits, drains, walls, or rock. For erosion to continue, the opening size must be sufficient for the adjacent base soil particles to pass through it. This worksheet assesses the joint/defect opening size that allows erosion to continue.

10.1. Base Soil Characterization

Step 1 characterizes the base material. The range of $D_{95}B$ of the base soil adjacent to the open joint, defect, or crack is obtained from the Base Gradation worksheet, where the finest and coarsest $D_{95}B$ of the adjacent base soil after regrading (if applicable) are interpolated using a logarithmic scale for particle size and linear scale for percent passing. Figure 35 is an example of step 1.

Step 1: Assess the gradation of the base soil adjacent to the open joint, defect, or crack		
Coarsest $D_{95}B$ after regrading (if applicable)	0.425	mm
Finest $D_{95}B$ after regrading (if applicable)	0.066	mm

Figure 35. Step 1 of Constricted Exit worksheet: Base soil characterization.

10.2. Open Joint, Defect, or Crack Characterization

Step 2 characterizes the open joint, defect, or crack, and the joint/defect opening size (*JOS*) is input. The user-specified *JOS* and range of $D_{95}B$ of the adjacent base soil are portrayed on a cumulative particle-size plot to visually compare their relative sizes, as shown in Figure 36. The y-axis (percent passing by weight) is truncated at 90 percent passing since only the particle-size diameter corresponding to 95 percent passing is used in the evaluation. The size of the open joint, defect, or crack is depicted with a vertical back line at the *JOS* and horizontal lines that extend infinitely smaller since a logarithmic scale is used. The range of $D_{95}B$ displays as a red horizontal line.

Step 2: Assess the opening size of the open joint, defect, or crack		
Joint/defect opening size, JOS	10	mm

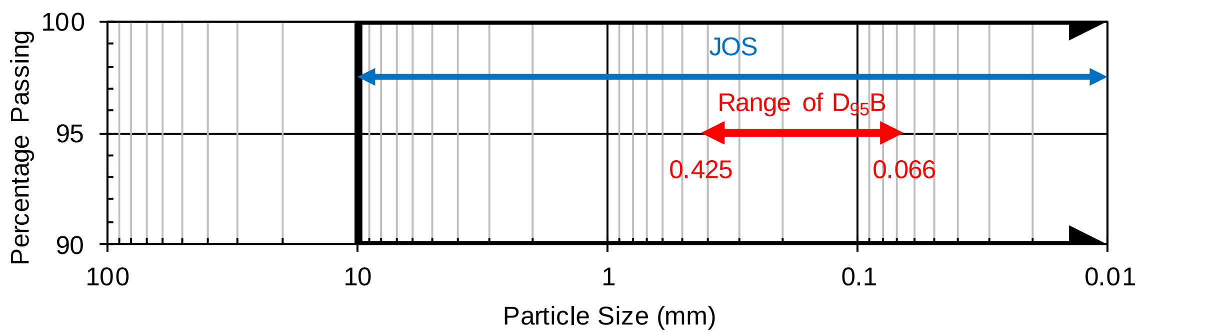


Figure 36. Step 2 of Constricted Exit worksheet: Effective opening size.

The plot options for this chart are illustrated in Figure 37. The minimum and maximum values for the x-axis (particle size) are user-specified.

Worksheet	Constricted Exit		
x-axis bounds			
minimum	0.01	◄ Enter minimum particle size.	Category Primary Min: 0.01
maximum	100	◄ Enter maximum particle size.	Category Primary Max: 100

Figure 37. Step 2 of Constricted Exit worksheet: Plot options.

10.3. Likelihood of Continuation

Step 3 estimates the probability of continuing erosion (P_{CE}) using the procedure of Fell and Foster (2023). The JOS that allows continuing erosion of the adjacent base soil (JOS_{CE}) is between $D_{95}B$ and $3D_{95}B$. Sherard et al. (1984) concluded that uniform filters act similar to laboratory sieves with an opening sieve size approximately equal to $D_{15}F/9$. The $D_{95}B$ criterion assumes the Foster and Fell (2001) continuing erosion criterion (see section 8.4) applies to erosion into an open joint, defect, or crack, and the crack width is equivalent to the filter opening size of the voids between the particles in a filter. The $3D_{95}B$ criterion is based on the JOS for cement grout to penetrate and flow along the opening of joints in rock.

The probabilities shown in Table 2 considered these limits. In the table, P_{CE} is a function the ratio of the *JOS* to the finest $D_{95}B$ of the adjacent base soil after regrading (if applicable). If $JOS/D_{95}B$ is less than 0.4, zero is displayed. If $JOS/D_{95}B$ is greater than or equal to 0.4 and less than 0.5, “<0.0001” is displayed. Intermediate values between 0.5 and 3.0 are interpolated using a z-variate scale for probability and a linear scale for the ratio $JOS/D_{95}B$.

Table 2.
Probability of continuing erosion for joint/defect opening size (Fell and Foster 2023).

$JOS/D_{95}B$	< 0.4	0.5	0.75	1.0	2.0	≥ 3.0
P_{CE}	0	0.0001	0.001	0.1	0.5	0.9

According to Fell and Foster (2023), these probabilities apply to erosion into open defects in the foundation and conduits or walls with steady flow conditions. Use higher probabilities for erosion into open defects in conduits or walls with dynamic flow conditions.

If the coarsest $D_{95}B$ of the adjacent base soil after regrading is less than or equal to the *JOS* (coarsest $D_{95}B \le JOS$), the proportion of the $D_{95}B$ finer than the *JOS* is 100 percent. If the finest $D_{95}B$ of the adjacent base soil after regrading is greater than or equal to the *JOS* (finest $D_{95}B \ge JOS$), the proportion of the $D_{95}B$ finer than the *JOS* is 0 percent. If the coarsest $D_{95}B$ of the adjacent base soil after regrading (if applicable) is greater than the *JOS* and the finest $D_{95}B$ after regrading (if applicable) is less than the *JOS*, the proportion of the $D_{95}B$ finer than the *JOS* is calculated as in Equation 6. Figure 38 is an example of step 3.

$$P_{CE} = \frac{\log_{10}(JOS) - \log_{10}(finest\ D_{95}B)}{\log_{10}(coarsest\ D_{95}B) - \log_{10}(finest\ D_{95}B)} \tag{6}$$

Step 3: Estimate the likelihood of continuation

$JOS / D_{95}B$	< 0.4	0.5	0.75	1.0	2.0	≥ 3.0
P_{CE}	0	0.0001	0.001	0.1	0.5	0.9

Probability of continuing erosion, P_{CE}	$JOS / D_{95}B$	P_{CE}
Coarsest $D_{95}B$ after regrading (if applicable)	23.53	9.00E-01
Finest $D_{95}B$ after regrading (if applicable)	152.63	9.00E-01

According to Fell and Foster (2023), Table 2 applies to erosion into open defects in the foundation and conduits or walls with steady flow conditions. Use higher probabilities for erosion into open defects in conduits or walls with dynamic flow conditions

If coarsest $D_{95}B$ after regrading (if applicable) ≤ JOS, proportion of $D_{95}B$ finer than JOS is 100 percent.

If coarsest $D_{95}B$ after regrading (if applicable) > JOS and finest $D_{95}B$ after regrading (if applicable) < JOS,

proportion of $D_{95}B$ finer than JOS is $\frac{\log_{10}(JOS) - \log_{10}(\text{finest } D_{95}B)}{\log_{10}(\text{coarsest } D_{95}B) - \log_{10}(\text{finest } D_{95}B)} \times 100\%$

If finest $D_{95}B$ after regrading (if applicable) ≥ JOS, proportion of $D_{95}B$ finer than JOS is 0 percent.

Proportion of $D_{95}B$ finer than JOS 100.0 percent

Note: Probabilities obtained from this method should not be used directly in risk assessments. Rather, the values should be used to help develop a list of more and less likely factors.

Figure 38. Step 3 of Constricted Exit worksheet: Probability of continuing erosion.

11. Permeability

This worksheet assesses whether the filter material meets the drainage criterion for permeability. It requires no user-specified input. Permeability is directly proportional to the square of the effective particle size with all other factors being equal. Typically, the permeability of a filter should be at least 16 to 25 times that of the base material. This criterion is generally met if $D_{15}F$ is larger than 4 to 5 times $D_{15}B$. In some very broadly graded base soils, this requirement may be difficult to meet.

11.1. Base Soil Characterization

Step 1 characterizes the base soil. FEMA (2011) indicates the coarsest $D_{15}B$ before regrading is used to evaluate permeability requirements. Step 1 obtains the coarsest $D_{15}B$ before regrading from the Base Gradation worksheet, where it is interpolated using a logarithmic scale for particle size and linear scale for percent passing. Figure 39 is an example of step 1.

Step 1: Assess the gradation of the coarsest base soil		
Coarsest $D_{15}B$ before regrading	0.007	mm

Figure 39. Step 1 of Permeability worksheet: Base soil characterization.

11.2. Filter Material Characterization

Step 2 characterizes the filter material. The finest $D_{15}F$ is obtained from the Filter Gradation worksheet, where it is interpolated using a logarithmic scale for particle size and linear scale for percent passing. Figure 40 is an example of step 2.

Step 2: Assess the gradation of the finest filter material		
Finest $D_{15}F$	0.505	mm

Figure 40. Step 2 of Permeability worksheet: Filter material characterization.

11.3. Permeability Criterion

The criterion for permeability is that the filter material has a minimum $D_{15}F$ that is an integer multiplier of the coarsest $D_{15}B$ before regrading but not less than 0.1 mm. USACE Engineer Manual (EM) 1110-2-1901 (2005) requires a multiplier of 3 to 5. However, USBR (2011) and National Resources Conservation Service (NRCS) (2017) require a multiplier of 5, which is considered the primary criterion on this worksheet. The minimum $D_{15}F$ of the filter material is calculated as in Equation 7.

$$D_{15}F \geq 5(D_{15}B) \text{ but not less than 0.1 mm} \tag{7}$$

where:

> $D_{15}F$ = particle-size diameter of the filter material corresponding to 15 percent passing on the cumulative particle-size distribution curve
> $D_{15}B$ = particle-size diameter of the base soil corresponding to 15 percent passing on the cumulative particle-size distribution curve before regrading

Step 3 evaluates the permeability criterion for integer multipliers ranging from 3 to 5. If the criterion is met, "Meets" displays next to the calculation. If the criterion is not met, "Fails" displays next to the calculation. A green background displays if the criterion is met, and an orange background displays if the criterion is not met. Based on the primary criterion using a multiplier of 5, a statement appears after the set of calculations indicating whether the filter material is sufficiently permeable to perform the required drainage function. Examples of the two possible scenarios for the primary filter criterion are shown in Figure 41 and Figure 42.

Step 3: Assess the permeability criterion for the filter material

Minimum allowable $D_{15}F \geq (3 \text{ to } 5)(D_{15}B)$ but not less than 0.1 mm

Note: Reclamation (2011) and NRCS (2017) require $D_{15}F \geq 5(D_{15}B)$ but not less than 0.1 mm.

$D_{15}F \geq 3(D_{15}B)$ but not less than 0.1 mm	0.022 mm		Fails
$D_{15}F \geq 4(D_{15}B)$ but not less than 0.1 mm	0.030 mm		Fails
$D_{15}F \geq 5(D_{15}B)$ but not less than 0.1 mm	0.037 mm	◄ Primary Criteria	Fails

Based on the primary criteria above, the filter material is not sufficiently permeable to perform the required drainage function.

Figure 41. Step 3 of Permeability worksheet: Primary permeability criteria not met.

Step 3: Assess the permeability criterion for the filter material

Minimum allowable $D_{15}F \geq (3 \text{ to } 5)(D_{15}B)$ but not less than 0.1 mm

Note: Reclamation (2011) and NRCS (2017) require $D_{15}F \geq 5(D_{15}B)$ but not less than 0.1 mm.

$D_{15}F \geq 3(D_{15}B)$ but not less than 0.1 mm	0.022 mm		Meets
$D_{15}F \geq 4(D_{15}B)$ but not less than 0.1 mm	0.030 mm		Meets
$D_{15}F \geq 5(D_{15}B)$ but not less than 0.1 mm	0.037 mm	◄ Primary Criteria	Meets

Based on the primary criteria above, the filter material is sufficiently permeable to perform the required drainage function.

Figure 42. Step 3 of Permeability worksheet: Primary permeability criteria met.

12. References

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Appendix A. Acronym List

BSC	Base Soil Category
CE	Continuing Erosion
CEF	Continuing Erosion Filter
CPD	Computer Program Document
EE	Excessive Erosion
FC	Fines Content
FEMA	Federal Emergency Management Agency
fm	Fine-to-Medium
HEC	Hydrologic Engineering Center
HW	Headwater
IWR	Institute for Water Resources
JOS	Joint/Defect Opening Size
NAVD88	North American Vertical Datum of 1988
NE	No Erosion
NEF	No-Erosion Filter
NGVD29	National Geodetic Vertical Datum of 1929
NRCS	National Resources Conservation Service
QC	Quality Control
RMC	Risk Management Center
SE	Some Erosion
UDF	User-Defined Function
UNSW	University of New South Wales
U.S.	United States
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture