RMC Soil Contact Erosion (Initiation) Toolbox

RMC Internal Erosion Suite

RMC-CPD-2023-03

November 2023

US Army Corps of Engineers®
Dam and Levee Safety Programs

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14. ABSTRACT
The spreadsheet tools contained in this toolbox assess the likelihood of initiation of soil contact erosion using the methods of Guidoux et al. (2010) for sand, silt, and sand/clay mixtures below gravel and Brauns (1985) for sand below gravel.

15. SUBJECT TERMS
Internal erosion, soil contact erosion, initiation, hydraulic condition

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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

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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 Soil Contact Erosion (Initiation) 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.

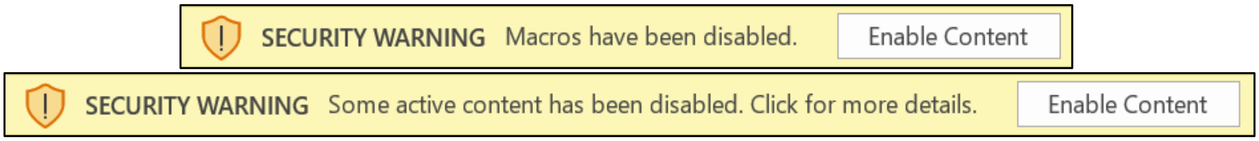


Figure 1. Security warning message bars with the “Enable Content” option to enable macros.

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

Soil contact erosion is defined as the selective erosion of fine particles from the contact with a coarser layer caused by flow passing through the coarser layer parallel to the contact. It is a scour mechanism like concentrated leak erosion through a crack, but the flow is through a coarse soil layer scouring finer materials in contact with the coarse layer. The field conditions necessary for soil contact erosion are uncommon—the cases that led to lab testing this process apparently were a result of silt levees placed on open-work gravels resulting in sinkholes or subsidence. Generally, soil contact erosion is not likely to lead to breach and is considered a contributing mechanism (e.g., can lead to internal migration and sinkhole development or form a roof/pipe for concentrated leak erosion).

The domain for evaluating initiation of soil contact erosion is defined by a geometric condition and a hydraulic condition. The geometric condition requires that the pores of the coarse soil layer be sufficiently large to allow fine soil particles to pass through, while the hydraulic condition requires that the flow velocity through the coarser layer be sufficient to detach the fine soil particles and transport them. Figure 8, adapted from Brauns (1985) in Robbins and Griffiths (2018), illustrates the influence of geometry and hydraulic conditions on the critical Froude number for erosion. In this figure, $D_{15}F$ is the particle-size diameter of the filter material (coarse or gravel layer) corresponding to 15 percent passing on the cumulative particle-size distribution curve, and $D_{85}B$ is the particle-size diameter of the base material (fine layer) corresponding to 85 percent passing on the cumulative particle-size distribution curve.

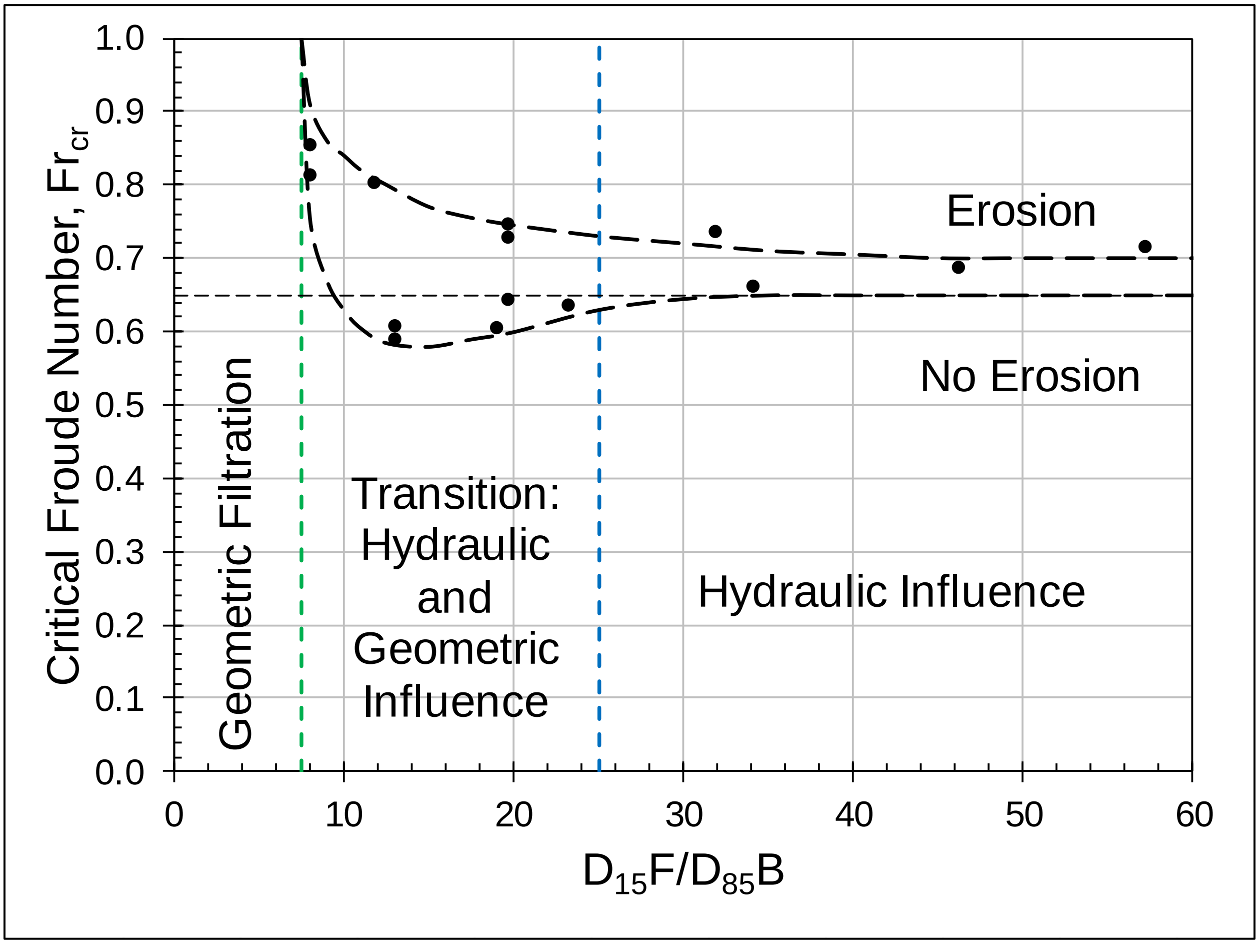


Figure 8. Influence of geometric and hydraulic conditions on critical Froude number for erosion (adapted from Brauns 1985).

In general, soils with $D_{15}F/D_{85}B$ ratios less than about 7.5 to 8 do not meet the geometric condition and are not susceptible to soil contact erosion. If the geometric condition is met, the critical Darcy velocity of the flow through the filter (coarse layer) at which erosion of the fine base soil is expected must be estimated. A transition zone exists as $D_{15}F/D_{85}B$ approaches the geometric condition in which the critical Darcy velocity depends on both geometric and hydraulic conditions.

Once $D_{15}F/D_{85}B$ becomes greater than about 25 to 30, purely hydraulic conditions control the erosion, and the critical Darcy velocity must be estimated from the method of either Guidoux et al. (2010) for sand, silt, and sand/clay mixtures below gravel or Brauns (1985) for sand below gravel as shown below for porosities of the gravel layer of 0.25 and 0.40. Most of the testing was performed on gravel with a porosity of about 0.40. In Figure 9, the Brauns (1985) relationship is equivalent to Guidoux et al. (2010) within the range of applicability.

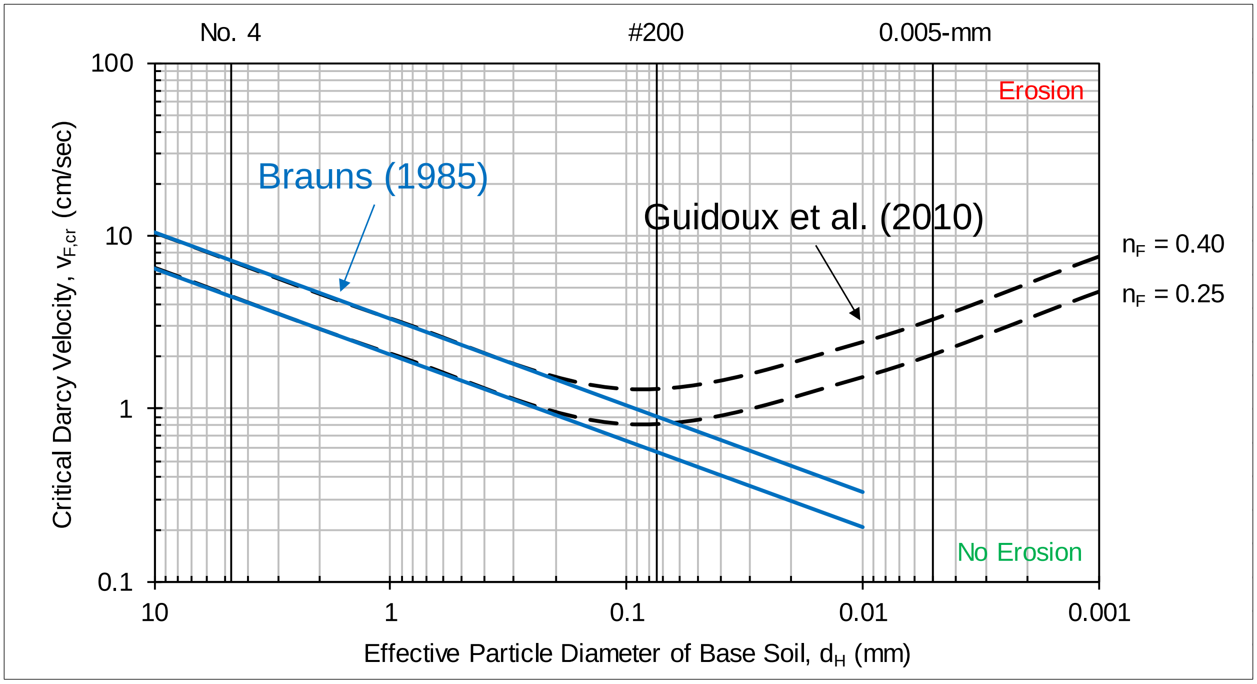


Figure 9. Critical Darcy velocity for initiation of soil contact erosion.

Applying these methods correctly requires understanding the context from which each method was developed, as the laboratory test conditions may vary from field conditions. For example, the Guidoux et al. (2010) and Brauns (1985) methods apply to gravel below fine soil. Experimental data with fine soil above gravel is limited. This phenomenon is complex and cannot be linked to riverine erosion. Influence of confining stress on critical Darcy velocity existed. Although measured critical Darcy velocities were of similar order of magnitude as gravel above fine soil (i.e., between 1 and 10 cm/s), the critical Darcy velocity can be much lower. For silt above gravel where erosion might be expected to initiate when silt particles fall into the gravel, initiation of soil contact erosion depends on the transport of particles, not by detachment. Therefore, neither method applies.

5. Gradation

This worksheet performs a particle-size analysis of the base soil. The particle-size analysis informs the effective particle diameter (d_H) for the Guidoux et al. (2010) method and the median particle diameter (d_{50}) for the Brauns (1985) method.

5.1. Coarsest Base Soil Characterization

Step 1 inputs the coarsest base soil gradation and calculates the effective particle diameter (d_H) and median particle diameter (d_{50}). The input includes sieve size (inches or sieve number), particle size (mm) for hydrometer analysis, and percent finer (by weight).

Use the drop-down list to select the sieve size that defines the gradation of the coarsest base soil. 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 base soil (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 coarsest base soil 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. This 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 10 illustrates the gradation input.

For each increment of the base soil gradation curve, the mass fraction (F_j as a decimal), average particle size (d_j using geometric mean), and F_j/d_j ratio are calculated. The calculations for each increment start in the second row of Figure 10, since an increment is defined by two consecutive particle sizes in the base soil gradation curve. For the first increment in Figure 10, the mass fraction of 0.100 is calculated as the difference between the mass passing the 2-inch sieve size and the mass passing the 1.5-inch sieve size (100 percent minus 90 percent), divided by 100 percent. The average particle size of 43.301 mm is calculated as the geometric mean of 50 mm (2-inch sieve) and 37.5 mm (1.5-inch sieve). The calculated F_j/d_j ratios for each increment of the base soil gradation curve are summed at the end of the table to use in step 3.

Step 1: Assess the gradation of the coarsest base soil

Sieve Size	D (mm)		F (percent)	F_j	d_j (mm)	F_j/d_j (1/mm)	
	Sieve	Hydrometer					
2-in	50		100.0				
1½-in	37.5		90.0	0.100	43.301	0.002	
1-in	25		70.0	0.200	30.619	0.007	
3/4-in	19		60.0	0.100	21.794	0.005	
1/2-in	12.5		48.0	0.120	15.411	0.008	
3/8-in	9.5		38.0	0.100	10.897	0.009	
No. 4	4.75		25.0	0.130	6.718	0.019	
No. 10	2		18.0	0.070	3.082	0.023	
No. 16	1.18		14.0	0.040	1.536	0.026	
No. 20	0.85		12.0	0.020	1.001	0.020	
No. 30	0.6		9.0	0.030	0.714	0.042	
No. 40	0.425		4.0	0.050	0.505	0.099	
No. 50	0.3		3.0	0.010	0.357	0.028	
No. 70	0.212		1.0	0.020	0.252	0.079	
No. 200	0.075		0.5	0.005	0.126	0.040	
	-			-	-	-	
	-			-	-	-	$\Sigma(F_j/d_j)$
	-			-	-	-	▼
	-			-	-	-	0.406

Figure 10. Gradation worksheet: Coarsest base soil gradation input and analysis.

5.2. Finest Base Soil Characterization

In step 2, the finest base soil gradation characterization is the same as the coarsest base soil gradation as shown in Figure 11.

Step 2: Assess the gradation of the finest base soil

Sieve Size	D (mm)		F (percent)	F_j	d_j (mm)	F_j/d_j (1/mm)	
	Sieve	Hydrometer					
2-in	50		100.0				
1½-in	37.5		100.0	0.000	43.301	0.000	
1-in	25		82.0	0.180	30.619	0.006	
3/4-in	19		70.0	0.120	21.794	0.006	
1/2-in	12.5		59.0	0.110	15.411	0.007	
3/8-in	9.5		49.0	0.100	10.897	0.009	
No. 4	4.75		35.0	0.140	6.718	0.021	
No. 10	2		28.0	0.070	3.082	0.023	
No. 16	1.18		24.0	0.040	1.536	0.026	
No. 20	0.85		22.0	0.020	1.001	0.020	
No. 30	0.6		17.0	0.050	0.714	0.070	
No. 40	0.425		13.0	0.040	0.505	0.079	
No. 50	0.3		9.0	0.040	0.357	0.112	
No. 70	0.212		3.0	0.060	0.252	0.238	
No. 200	0.075		1.5	0.015	0.126	0.119	
	-			-	-	-	
	-			-	-	-	$\Sigma(F_j/d_j)$
	-			-	-	-	▼
	-			-	-	-	0.735

Figure 11. Gradation worksheet: Finest base soil gradation input and analysis.

5.3. Particle Size Analysis

Step 3 plots the user-specified coarsest and finest base soil gradations with particle size on the x-axis and percent passing by weight on the y-axis as shown in Figure 12. Vertical grid lines correspond to the particle-size boundaries for boulders, cobbles, coarse gravel, fine gravel, coarse sand, medium sand, fine sand, and clay or silt.

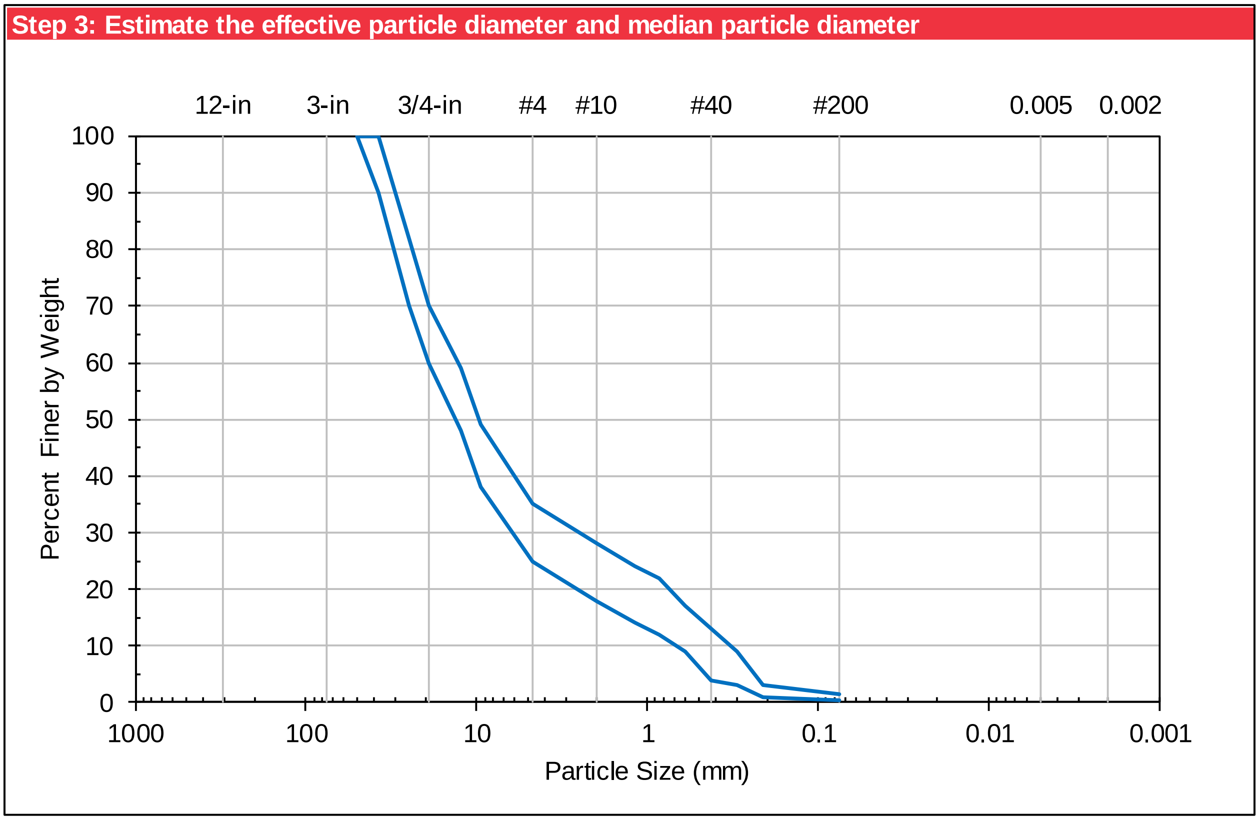


Figure 12. Gradation worksheet: Gradation plot.

The particle-size analysis for the user-specified gradations from step 1 and step 2 are summarized as shown in Figure 13. The gravel percentage (including coarse and fine gravel percentages), sand percentage (including coarse, medium, and fine sand percentages), and fines content (FC) (including estimated silt and clay percentages) for the coarsest and finest gradations of the base soil are calculated according to the Unified Soil Classification System (American Society of Testing and Materials [ASTM] D2487). An average percentage is also calculated.

The effective particle diameter of the base soil (d_H) is the reciprocal of the sum of the F_j/d_j ratios from steps 1 and 2 as shown in Equation 1.

$$d_H = \left(\sum_{j=1}^{m} \frac{F_j}{d_j}\right)^{-1} \quad (1)$$

where:

F_j (-) = mass fraction of the increment j of the base soil gradation curve
d_j (mm) = average particle size of the increment j of the base soil gradation curve

The minimum and maximum values correspond to the finest and coarsest base soil gradation, respectively. The mean value corresponds to the geometric mean of the minimum and maximum values.

The median particle diameter of the base soil (d_{50}) is the particle size corresponding to 50 percent finer (by weight). The minimum and maximum values are interpolated using logarithmic scale for particle size and linear scale for percent finer by weight for the finest and coarsest base soil gradations, respectively. The mean value corresponds to the geometric mean of the minimum and maximum values.

Particle-Size Analysis	Coarse	Fine	Average
Gravel (%): 3-in (75 mm) to 4.75-mm	75.0	65.0	70.0
Coarse Gravel (%): 3-in (75-mm) to ¾-in (19-mm)	40.0	30.0	35.0
Fine Gravel (%): ¾-in (19-mm) to 4.75-mm	35.0	35.0	35.0
Sand (%): 4.75 mm to 0.075 mm	24.5	33.5	29.0
Coarse Sand (%): 4.75-mm to 2.00-mm	7.0	7.0	7.0
Medium Sand (%): 2.00-mm to 0.425-mm	14.0	15.0	14.5
Fine Sand (%): 0.425-mm to 0.075-mm	3.5	11.5	7.5
Fines Content (%): Smaller than 0.075-mm	0.5	1.5	1.0
Silt (%): 0.075-mm to 0.002-mm	#N/A	#N/A	#N/A
Clay (%): Finer than 0.002-mm	#N/A	#N/A	#N/A
Use the effective particle diameter of the base soil with Guidoux et al. (2010) methodology			
Reasonable Estimate	Minimum	Mean	Maximum
Effective particle diameter, d_H (mm) = $1 / \Sigma(F_j/d_j)$	1.360	1.829	2.460
Use the median particle diameter of the base soil with Brauns (1985) methodology			
Reasonable Estimate	Minimum	Mean	Maximum
Median particle diameter, d_{50} (mm)	9.764	11.440	13.403

Figure 13. Gradation worksheet: Summary of particle-size analysis.

6. Guidoux et al. Method

Based on experimental data, Guidoux et al. (2010) proposed a relationship to estimate the critical Darcy velocity for initiation of soil contact erosion of fine soil (sand, silt, and sand/clay mixtures) below gravel as a function of effective particle diameter of the fine soil, porosity of the gravel layer, and Darcy velocity of flow through the gravel layer. In Figure 14, the upper relationship is for a filter (gravel layer) porosity of 0.40, and the lower relationship is for a filter (gravel layer) porosity of 0.25.

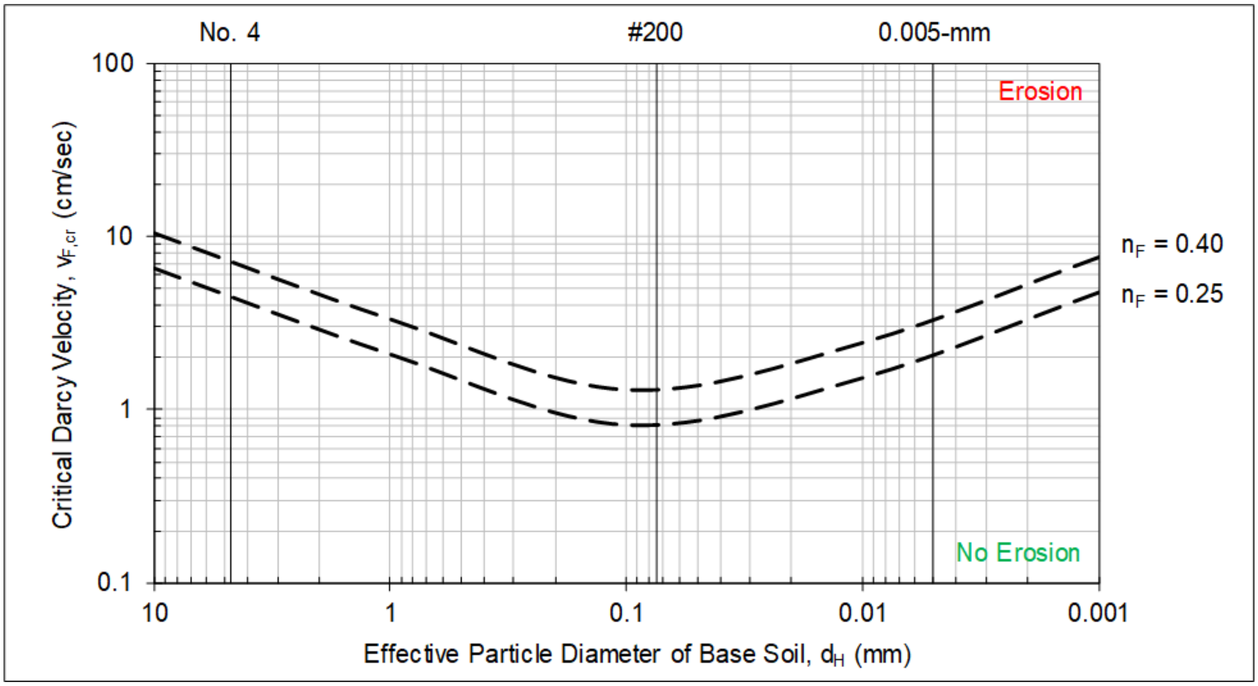
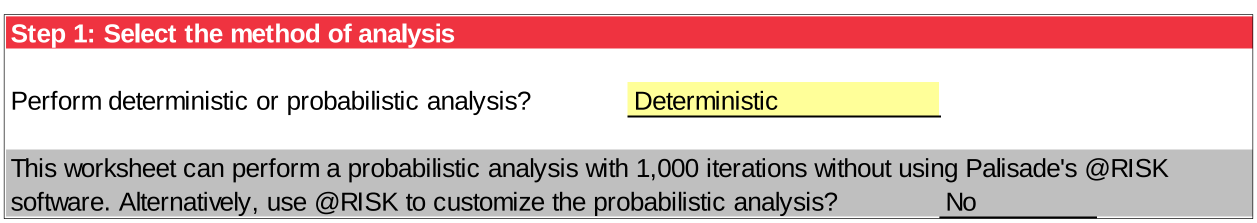


Figure 14. Critical Darcy velocity for Guidoux et al. (2010) method.

6.1. Method of Analysis

In step 1, use the drop-down list to select the method of analysis (probabilistic or deterministic). There are two options for probabilistic analysis. The first performs 1,000 iterations (judged adequate for most applications) without using Palisade's @RISK software. This provides flexibility if an @RISK software license is not available. The second uses @RISK to customize the probabilistic analysis. Use the drop-down list to select Yes if @RISK is used and No if @RISK is not used. Figure 15 through Figure 17 illustrate the three possible scenarios.


Step 1: Select the method of analysis

Perform deterministic or probabilistic analysis? Deterministic

This worksheet can perform a probabilistic analysis with 1,000 iterations without using Palisade's @RISK software. Alternatively, use @RISK to customize the probabilistic analysis? No

Figure 15. Step 1 of Guidoux et al. worksheet: Deterministic analysis.

Step 1: Select the method of analysis	
Perform deterministic or probabilistic analysis?	Probabilistic
This worksheet can perform a probabilistic analysis with 1,000 iterations without using Palisade's @RISK software. Alternatively, use @RISK to customize the probabilistic analysis?	No

Figure 16. Step 1 of Guidoux et al. worksheet: Probabilistic analysis without using @RISK.

Step 1: Select the method of analysis	
Perform deterministic or probabilistic analysis?	Probabilistic
This worksheet can perform a probabilistic analysis with 1,000 iterations without using Palisade's @RISK software. Alternatively, use @RISK to customize the probabilistic analysis?	Yes

Figure 17. Step 1 of Guidoux et al. worksheet: Probabilistic analysis using @RISK.

6.2. Base Soil Characterization

Step 2 characterizes the base soil. The input includes specific gravity of soil particles (G_s) and effective particle diameter of the base soil (d_H). The effective particle diameter of the base soil (d_H) is informed by the calculated values on the Gradation worksheet. The empirical coefficient (β) used in the equation for critical Darcy velocity is the best-fit value of 5.30E-09 m^2 from Guidoux et al. (2010) based on experimental data.

The selections in step 1 affect the input for step 2, and cells that do not apply have a gray background. These cells are not used in subsequent calculations even if data is present.

For deterministic analysis, input only the most likely value of d_H. The mean value used for subsequent calculations is the most likely (or mode) value. Figure 18 illustrates the deterministic input.

Step 2: Characterize the base soil

Specific gravity of soil particles, G_s	2.65	
Empirical coefficient, β	5.30E-09	m^2

Parameter	Units	Minimum	Most Likely	Maximum
Effective particle diameter, d_H	mm	1.360	1.829	2.460

Parameter	Units	Mean	@RISK Formula	Mean
d_H	mm	#NAME?		1.829

Figure 18. Step 2 of Guidoux et al. worksheet: Deterministic input.

For probabilistic analysis without using @RISK, input the minimum and maximum values in addition to the most likely value, and a triangular distribution represents d_H. The mean value used in subsequent calculations is the average of the minimum, most likely, and maximum values. Figure 19 illustrates the probabilistic input without using @RISK.

Step 2: Characterize the base soil

Specific gravity of soil particles, G_s	2.65	
Empirical coefficient, β	5.30E-09	m^2

Parameter	Units	Minimum	Most Likely	Maximum
Effective particle diameter, d_H	mm	1.360	1.829	2.460

Parameter	Units	Mean	@RISK Formula	Mean
d_H	mm	#NAME?		1.883

Figure 19. Step 2 of Guidoux et al. worksheet: Probabilistic input without using @RISK.

For probabilistic analysis using @RISK, input the minimum, most likely, and maximum values of d_H, and use an @RISK formula for a triangular distribution in the third column as a default. Alternatively, input a valid @RISK distribution in lieu of this default formula, and the user-specified input displays in the fourth column. The mean value used in subsequent calculations is the mean for the @RISK distribution entered in the third column. Figure 20 illustrates the probabilistic input using @RISK.

Step 2: Characterize the base soil

Specific gravity of soil particles, G_s	2.65	
Empirical coefficient, β	5.30E-09	m^2

Parameter	Units	Minimum	Most Likely	Maximum
Effective particle diameter, d_H	mm	1.360	1.829	2.460

Parameter	Units	Mean	@RISK Formula	Mean
d_H	mm	1.883	=@RiskTriang(F26,G26,H26)	1.883

Figure 20. Step 2 of Guidoux et al. worksheet: Probabilistic input using @RISK.

If using @RISK to perform probabilistic analysis, delete unnecessary calculation worksheets because the simulation is performed for all worksheets in the workbook, which is time consuming. If cycling through iterations using @RISK, the displayed results are no longer mean values of the random variables; they are the selected iteration's values.

6.3. Filter (Gravel Layer) Characterization

Step 3 characterizes the coarse layer. The input includes the porosity (n_F) and horizonal permeability (k_h) of the coarse layer (filter), typically gravel for this internal erosion process. A reasonable range of porosity for gravel is between 0.25 and 0.40. The coarse soils evaluated by Guidoux et al. (2010) had porosity values between 0.40 and 0.43, near the upper range. However, values of porosity less than 0.40

result in lower values of critical Darcy velocity for initiation of soil contact erosion. Therefore, t critical Darcy velocity is evaluated using discrete porosity values of 0.25 and 0.40.

The selections in step 1 affect the input for step 3, and cells that do not apply have a gray background. These cells are not used in subsequent calculations even if data is present.

For deterministic analysis, input only the most likely value for k_h. The mean value used for subsequent calculations is the most likely (or mode) value. Figure 21 illustrates the deterministic input.

Step 3: Characterize the filter (gravel layer)

Porosity of gravel layer, n_F 0.25 to 0.40

Parameter	Units	Minimum	Most Likely	Maximum
Horizontal permeability, k_h	cm/sec	1.00E+00	1.00E+01	2.50E+01

Parameter	Units	Mean	@RISK Formula	Mean
k_h	cm/sec	#NAME?		1.00E+01

Figure 21. Step 3 of Guidoux et al. worksheet: Deterministic input.

For probabilistic analysis without using @RISK, input the minimum and maximum values in addition to the most likely value, and a triangular distribution represents k_h. The mean value used in subsequent calculations is the average of the minimum, most likely, and maximum values. Figure 22 illustrates the probabilistic input without using @RISK.

Step 3: Characterize the filter (gravel layer)

Porosity of gravel layer, n_F 0.25 to 0.40

Parameter	Units	Minimum	Most Likely	Maximum
Horizontal permeability, k_h	cm/sec	1.00E+00	1.00E+01	2.50E+01

Parameter	Units	Mean	@RISK Formula	Mean
k_h	cm/sec	#NAME?		1.20E+01

Figure 22. Step 3 of Guidoux et al. worksheet: Probabilistic input without using @RISK.

For probabilistic analysis using @RISK, input the minimum, most likely, and maximum values of k_h, and use an @RISK formula for a triangular distribution in the third column as a default. Alternatively, input a valid @RISK distribution in lieu of this default formula, and the user-specified input displays in the fourth column. The mean value used for subsequent calculations is the mean for the @RISK distribution entered in the third column. Figure 23 illustrates the probabilistic input using @RISK.

Step 3: Characterize the filter (gravel layer)				
Porosity of gravel layer, n_F		0.25 to 0.40		
Parameter	Units	Minimum	Most Likely	Maximum
Horizontal permeability, k_h	cm/sec	1.00E+00	1.00E+01	2.50E+01

Parameter	Units	Mean	@RISK Formula	Mean
k_h	cm/sec	1.20E+01	=@RiskTriang(F40,G40,H40)	1.20E+01

Figure 23. Step 3 of Guidoux et al. worksheet: Probabilistic input using @RISK.

If using @RISK to perform probabilistic analysis, delete unnecessary calculation worksheets because the simulation is performed for all worksheets in the workbook, which is time consuming. If cycling through iterations using @RISK, the displayed results are no longer mean values of the random variables; they are the selected iteration's values.

6.4. Critical Darcy Velocity for Initiation of Soil Contact Erosion

Step 4 calculates the critical Darcy velocity ($v_{F,cr}$) for initiation of soil contact erosion for sand, silt, and sand/clay mixtures below gravel as shown in Equation 2.

$$v_{F,cr}\ (m/s) = Fr_{cr} n_F \sqrt{\left(\frac{\rho_s - \rho_w}{\rho_w}\right) g d_H \left(1 + \left(\frac{\beta}{{d_H}^2}\right)\right)} \qquad (2)$$

where:

Fr_{cr} = critical Froude number (0.65)
n_F = porosity of the filter (gravel layer)
ρ_s = density of the base soil particles (sand, silt, or sand/clay mixtures)
ρ_w = density of water
g = acceleration of gravity
d_H = effective particle diameter of the base soil (sand, silt, or sand/clay mixtures)
β = empirical coefficient (best fit value of 5.3E-09 m^2 from experimental data)

Since it is easier to estimate the specific gravity of soil particles than the submerged density of soil particles, the following substitution in Equation 3is made to the equation for $v_{F,cr}$.

$$\frac{\rho_s - \rho_w}{\rho_w} = \frac{\rho_s'}{\rho_w} = G_s - 1 \qquad (3)$$

where:

G_s = specific gravity of the base soil particles (sand, silt, or sand/clay mixtures)

Therefore, Equation 4 shows that the equation for $v_{F,cr}$ can be simplified to:

$$v_{F,cr}\ (m/s) = Fr_{cr} n_F \sqrt{(G_s - 1) g d_H \left(1 + \left(\frac{\beta}{{d_H}^2}\right)\right)} \tag{4}$$

The critical Froude number of 0.7 recommended by Guidoux et al. (2010) differs from the value of 0.65 recommended by Brauns (1985). It is unclear if this is due to rounding. As previously discussed, a value of 0.65 provides a reasonable threshold for erosion and results in a lower critical Darcy velocity than Guidoux et al. (2010). Critical Darcy velocities are calculated for filter (gravel layer) porosities of 0.25 and 0.40, providing an upper and lower estimate as shown in Figure 24.

Based on experimental data, Guidoux et al. (2010) indicated that some soils exhibited similar critical Darcy velocities for initiation of soil contact erosion despite having significantly different median particle diameters (d_{50}), while other soils exhibited similar critical Darcy velocities for initiation of soil contact erosion despite having similar d_{50} values. Therefore, Guidoux et al. (2010) concluded that d_{50} is not a relevant soil characteristic for estimating critical Darcy velocity for fine-grained soils, and the effective particle diameter (d_H) defined by Kozeny (1953) is a more representative particle-size description for a base soil.

Step 4: Estimate the critical Darcy velocity for initiation of soil contact erosion		
Critical Darcy velocity, $v_{F,cr}$ (m/sec) = $(Fr_{cr})(n_F)[(\rho_s'/\rho_w)(g)(d_H)(1 + \beta/{d_H}^2)]^{0.5}$ where Fr_{cr} = critical Froude number		
$v_{F,cr}$ (m/sec) = $0.65(n_F)[(G_s - 1)(g)(d_H)(1 + \beta/{d_H}^2)]^{0.5}$	2.84	cm/sec for n_F = 0.25
using lower bound of range of Fr_{cr} from 0.65 to 0.70	4.54	cm/sec for n_F = 0.40

Figure 24. Step 4 of Guidoux et al. worksheet: Critical Darcy velocity.

6.5. Darcy Velocity of Flow in Filter (Gravel Layer)

Step 5 calculates the average hydraulic gradient (i) of flow in the filter (gravel layer) by dividing the net hydraulic head by the user-specified seepage path length as shown in Equation 5.

$$i = \frac{\Delta H}{L} = \frac{HW - TW}{L} \tag{5}$$

where:

HW = headwater level
TW = tailwater level
L = seepage path length

The Darcy velocity (v) of flow in the filter (gravel layer) is calculated by multiplying the horizontal permeability of the filter (gravel layer) by the average hydraulic gradient as shown in Equation 6.

$$v = k_h i \tag{6}$$

where:

k_h = horizontal permeability of the filter (gravel layer)
i = hydraulic gradient in the filter (gravel layer)

The Darcy velocity for each headwater and tailwater combination is summarized in a table for the minimum, mode, maximum, and mean k_h of the filter (gravel layer), as shown in Figure 25. For deterministic analysis, the mean Darcy velocity is calculated using the most likely value of k_h from step 3. For probabilistic analysis without using @RISK, the mean Darcy velocity is calculated using the mean k_h obtained from a triangular distribution of the minimum, most likely, and maximum values of k_h in step 3. For probabilistic analysis using @RISK, the mean Darcy velocity is calculated using the mean k_h obtained from the user-specified distribution of the minimum, most likely, and maximum values of k_h in step 3.

Step 5: Estimate the Darcy velocity of flow in the gravel layer

Darcy velocity, $v = k_h i$

Seepage path length, L 125.0 ft
Hydraulic gradient, i = Δh/L = (HW − TW)/L

HW (ft)	201.6	213.5	221.0	228.5	231.0	235.0	239.0
i	0.093	0.188	0.248	0.308	0.328	0.360	0.392
v_{min} (cm/sec)	0.09	0.19	0.25	0.31	0.33	0.36	0.39
v_{mode} (cm/sec)	0.93	1.88	2.48	3.08	3.28	3.60	3.92
v_{max} (cm/sec)	2.32	4.70	6.20	7.70	8.20	9.00	9.80
v_{mean} (cm/sec)	1.11	2.26	2.98	3.70	3.94	4.32	4.70

Figure 25. Step 5 of Guidoux et al. worksheet: Darcy velocity.

6.6. Likelihood of Initiation of Soil Contact Erosion

Step 6 compares the calculated Darcy velocity of flow in the filter (gravel layer) to the critical Darcy velocity for initiation of soil contact erosion. The factor of safety (FS) against initiation of soil contact erosion is calculated as shown in Equation 7.

$$FS = \frac{v_{F,cr}}{v} \tag{7}$$

where:

$v_{F,cr}$ = critical Darcy velocity for initiation of soil contact erosion
v = Darcy velocity of flow in the filter (gravel layer)

For deterministic analysis, the mean Darcy velocity of flow in the filter (gravel layer) is plotted as a function of headwater level and mean effective particle diameter of the base soil (d_H). Reference lines for the critical Darcy velocity of flow through the filter (gravel layer) for porosities of 0.25 and 0.40 display as dashed lines. When a Darcy velocity at a given headwater level plots above the line of critical Darcy velocity based on the porosity of the filter (gravel layer), the FS is greater than 1, and initiation of soil contact erosion is not predicted. Figure 26 illustrates the graphical output of Darcy velocity for deterministic analysis.

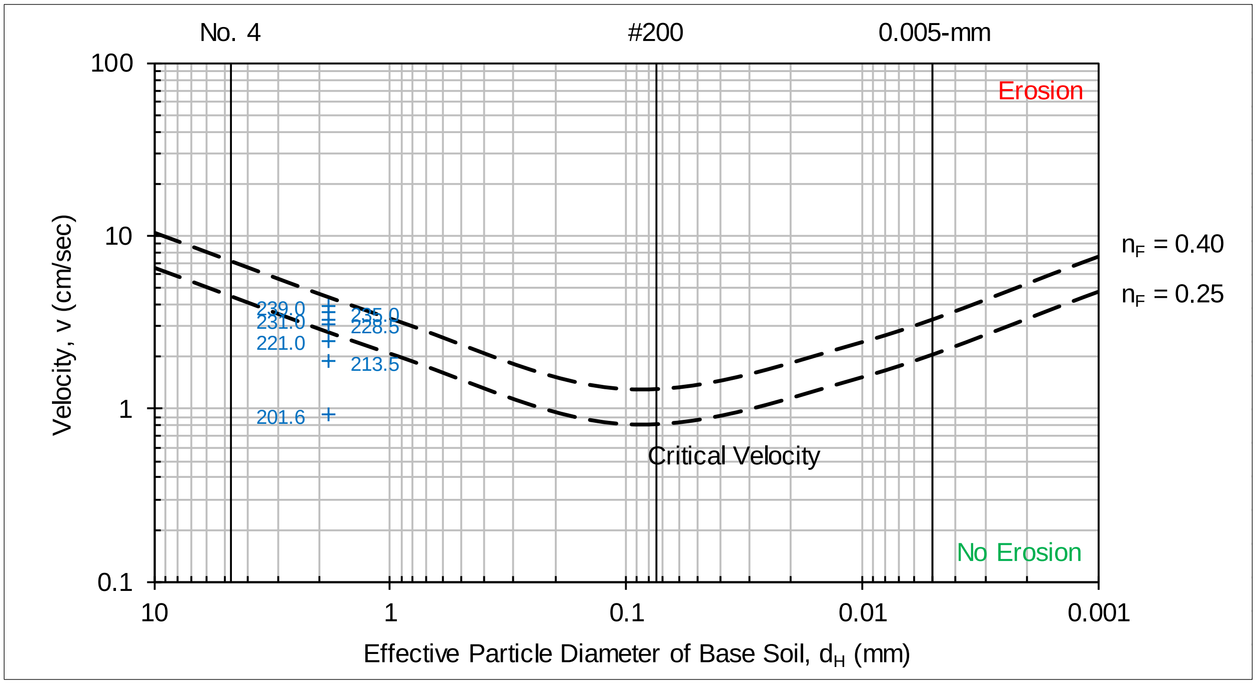


Figure 26. Step 6 of Guidoux et al. worksheet: Graphical output of Darcy velocity for deterministic analysis.

For probabilistic analysis, a black box is also plotted showing the distribution limits for effective particle diameter of the base soil and Darcy velocity of flow in the filter (gravel layer). Reference lines for the critical Darcy velocity of flow through the filter (gravel layer) for porosities of 0.25 and 0.40 display as dashed lines. Initiation of soil contact erosion is predicted for effective particle diameters and headwater combinations within the black box plotting above the line corresponding to the critical Darcy velocity being evaluated. Figure 27 illustrates the graphical output of Darcy velocity for probabilistic analysis.

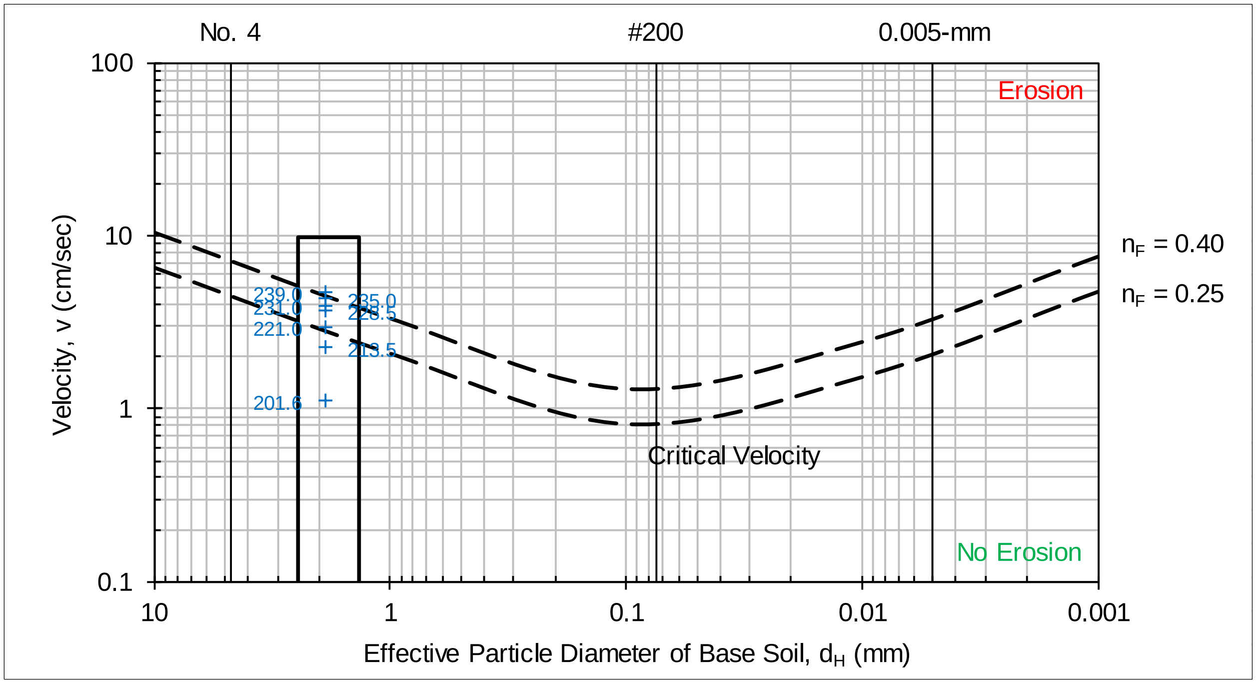


Figure 27. Step 6 of Guidoux et al. worksheet: Graphical output of Darcy velocity for probabilistic analysis.

Figure 28 illustrates the plot options for this chart. The minimum and maximum values for the y-axis (velocity) and minimum and maximum values for the x-axis (effective particle diameter of the base soil) are user-specified.

Worksheet	Guidoux et al.		
y-axis bounds			
minimum	0.10	◄ Enter minimum velocity.	Value Primary Min: 0.1
maximum	100	◄ Enter maximum velocity.	Value Primary Max: 100
x-axis bounds			
minimum	0.001	◄ Enter minimum effective diameter.	Category Primary Min: 0.001
maximum	10	◄ Enter maximum effective diameter.	Category Primary Max: 10

Figure 28. Step 6 of Guidoux et al. worksheet: Plot options of Darcy velocity for graphical output.

For deterministic analysis, the FS is calculated for filter (gravel layer) porosities of 0.25 and 0.40 using the most likely values of the random variables and summarized in separate tables. Cells that do not apply have a gray background. For probabilistic analysis, the FS is calculated as described for the deterministic analysis but for the mean values of the random variables, and multiple iterations are performed by sampling the distributions in step 6. The probability of initiation is equal to the percentage of iterations that resulted in a FS less than 1 [(P(FS < 1)]. For probabilistic analysis performed without using @RISK, 1,000 iterations are used. For probabilistic analysis using @RISK, the number of iterations is user-specified, and “@RISK” displays in parentheses after the number of iterations for this scenario. If cycling through iterations using @RISK, the displayed results are no longer mean values; they are the selected iteration's values. For deterministic and probabilistic analyses, cells with FS less than 1 have an orange background. Figure 29 illustrates the deterministic tabular output, and Figure 30 illustrates the probabilistic tabular output without using @RISK.

Factor of safety against initiation of soil contact erosion, FS = $v_{F,cr}/v$

Probability of a factor of safety against initiation of soil contact erosion less than 1, P(FS < 1)

Iterations: #N/A

Likelihood of soil contact erosion for n_F = 0.25

HW (ft)	201.6	213.5	221.0	228.5	231.0	235.0	239.0
FS	3.015	1.488	1.128	0.909	0.853	0.777	0.714
P(FS < 1)	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Likelihood of soil contact erosion for n_F = 0.40

HW (ft)	201.6	213.5	221.0	228.5	231.0	235.0	239.0
FS	4.825	2.382	1.805	1.454	1.365	1.244	1.142
P(FS < 1)	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

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

Figure 29. Step 6 of Guidoux et al. worksheet: Tabular output for deterministic analysis.

Factor of safety against initiation of soil contact erosion, FS = $v_{F,cr}/v$

Probability of a factor of safety against initiation of soil contact erosion less than 1, P(FS < 1)

Iterations: 1000

Likelihood of soil contact erosion for n_F = 0.25

HW (ft)	201.6	213.5	221.0	228.5	231.0	235.0	239.0
FS	2.550	1.258	0.954	0.768	0.721	0.657	0.604
P(FS < 1)	0.000	0.251	0.494	0.676	0.722	0.770	0.812

Likelihood of soil contact erosion for n_F = 0.40

HW (ft)	201.6	213.5	221.0	228.5	231.0	235.0	239.0
FS	4.079	2.014	1.526	1.229	1.154	1.052	0.966
P(FS < 1)	0.000	0.010	0.128	0.272	0.319	0.411	0.485

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

Figure 30. Step 6 of Guidoux et al. worksheet: Tabular output for probabilistic analysis without using @RISK.

At the end of step 6, summary plots are generated. The first plot is the mean FS against initiation of soil contact erosion as a function of headwater level. FS is displayed for filter (gravel layer) porosities of 0.25 (blue line) and 0.40 (green line). If cycling through iterations using @RISK, the displayed results are no longer mean values; they are the selected iteration's values. A horizontal reference line displays in black for a FS of 1.0.

Figure 31 illustrates graphical output for deterministic analysis.

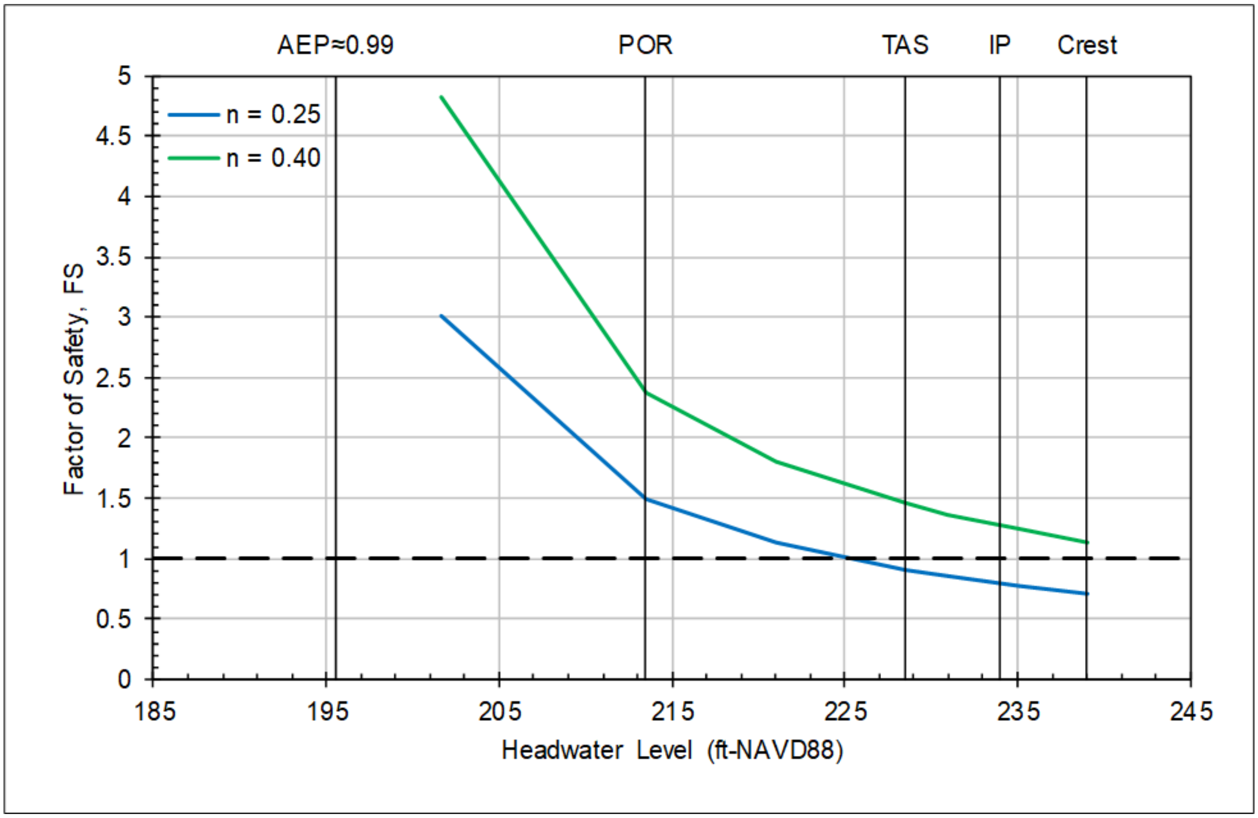


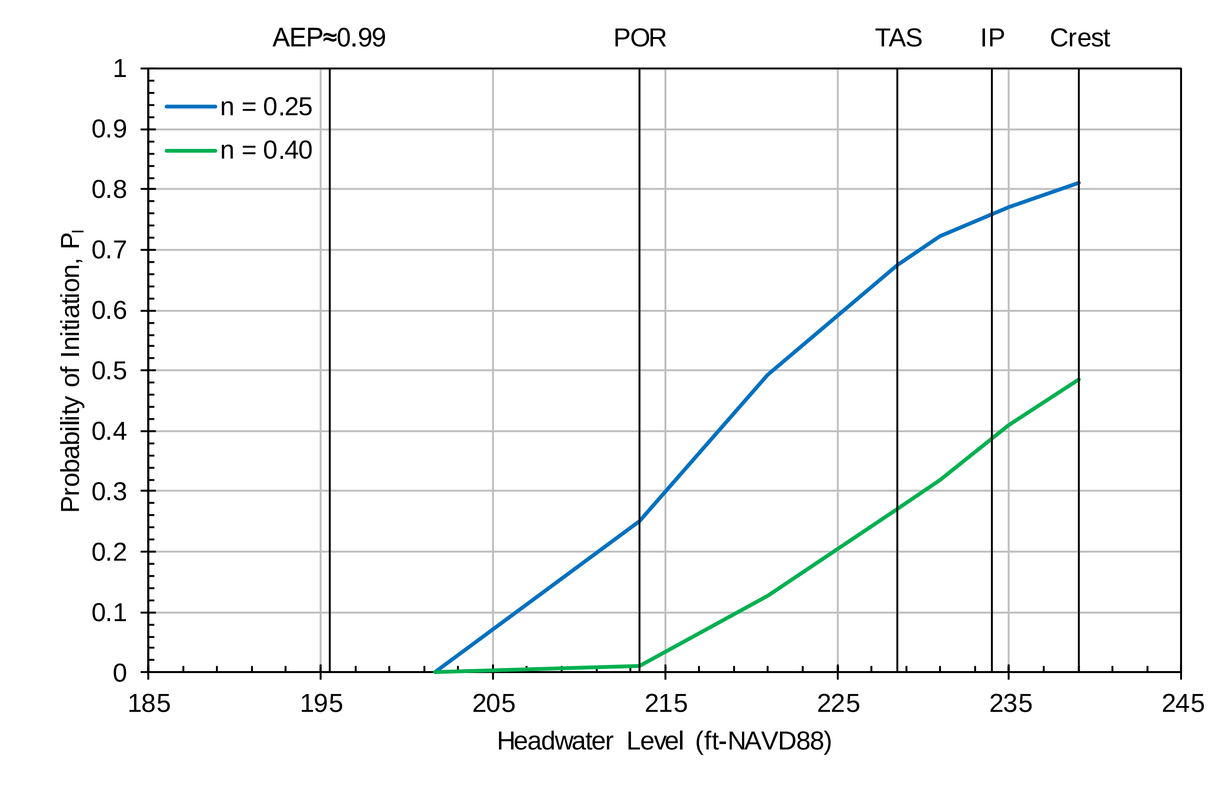
Figure 31. Step 6 of Guidoux et al. worksheet: Graphical output for factor of safety.

Figure 32 illustrates the plot options for this chart. The maximum value for the y-axis (FS against initiation of soil contact erosion) and minimum and maximum values for the x-axis (headwater level) are user-specified. Users can input up to five vertical reference elevations, and user-specified labels display at the top of the chart.

Worksheet	Guidoux et al.						
y-axis bounds							
minimum	0				Value Primary Min: 0		
maximum	5.0	◄ Enter maximum FS.			Value Primary Max: 5		
x-axis bounds							
minimum	185.0	◄ Enter minimum headwater level.			Category Primary Min: 185		
maximum	245.0	◄ Enter maximum headwater level.			Category Primary Max: 245		
Enter up to 5 vertical reference lines for headwater levels of interest.							
AEP≈0.99	POR	TAS	IP	Crest	◄ Enter headwater description.		
195.5	213.5	228.5	234.0	239.0	◄ Enter headwater level.		

Figure 32. Step 6 of Guidoux et al. worksheet: Plot options for factor of safety.

The second plot is the probability of initiation of soil contact erosion as a function of headwater level. For deterministic analysis, a probability of initiation of soil contact erosion is not calculated and this plot has a gray background. For probabilistic analysis, the mean probability of initiation of soil contact erosion is plotted for filter (gravel layer) porosities of 0.25 (blue line) and 0.40 (green line). If cycling through iterations using @RISK, this plot has a gray background because the probability of initiation cannot be calculated from a single iteration. Similarly, this plot has a gray background for deterministic analysis. Figure 33 illustrates the graphical output for probabilistic analysis.



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

Figure 33. Step 6 of Guidoux et al. worksheet: Graphical output for probabilistic analysis.

Figure 34 illustrates the plot options for this chart. The vertical reference elevations and minimum and maximum values for the x-axis (headwater level) are the same as the previous chart. Only the maximum value for the y-axis (probability of initiation of soil contact erosion) is user-specified.

Worksheet	Guidoux et al.		
y-axis bounds			
minimum	0		Value Primary Min: 0
maximum	1.0	◄ Enter maximum probability.	Value Primary Max: 1
x-axis bounds			
minimum	185.0	◄ Enter minimum headwater level.	Category Primary Min: 185
maximum	245.0	◄ Enter maximum headwater level.	Category Primary Max: 245

Figure 34. Step 6 of Guidoux et al. worksheet: Plot options for probability of initiation.

6.7. Headwater Level for Initiation of Soil Contact Erosion

Step 7 calculates the headwater level for initiation of soil contact erosion for filter (gravel layer) porosity values of 0.25 and 0.40. The results for different combinations of horizontal permeability of the filter (gravel layer) and critical Darcy velocity are linearly interpolated from the tables in step 6. The first table (Distribution) considers the combinations created by the distribution inputs in steps 2 and 3. The second table (Mean) considers the mean horizontal permeability of the filter (gravel layer) and mean critical Darcy velocity (based on effective particle diameter) and is available for both deterministic and probabilistic analyses. If the critical Darcy velocity is less than the Darcy velocity for the minimum specified headwater level, the headwater level for initiation so indicates. If the critical Darcy velocity is greater than the Darcy velocity for the maximum specified headwater level or if the Darcy velocity does not increase with an increase in headwater level (e.g., because of an increase in tailwater level), the headwater level for initiation cannot be calculated, and an error displays. For deterministic analysis, the mean value in the second table is equal to the most likely (or mode) value. Figure 35 and Figure 36 illustrate the critical headwater levels for deterministic and probabilistic analyses, respectively.

Step 7: Estimate the headwater level for initiation of soil contact erosion

Distribution — Headwater Level (ft) for $v > v_{F,cr}$

k_h (cm/sec)	$v_{F,cr}$ (cm/sec) for $n_F = 0.25$			$v_{F,cr}$ (cm/sec) for $n_F = 0.40$		
	2.41	2.80	3.24	3.86	4.48	5.19
1.00E+00	-	-	-	-	-	-
1.00E+01	220.2	225.0	230.6	238.3	-	-
2.50E+01	202.1	204.0	206.2	209.3	212.4	216.0

Mean — Headwater Level (ft) for $v > v_{F,cr}$

k_h (cm/sec)	$v_{F,cr}$ (cm/sec) for $n_F = 0.25$			$v_{F,cr}$ (cm/sec) for $n_F = 0.40$		
		2.80			4.48	
1.00E+01		225.0			-	

Figure 35. Step 7 of Guidoux et al. worksheet: Critical headwater level for deterministic analysis.

Step 7: Estimate the headwater level for initiation of soil contact erosion

Distribution — Headwater Level (ft) for $v > v_{F,cr}$

k_h (cm/sec)	$v_{F,cr}$ (cm/sec) for $n_F = 0.25$			$v_{F,cr}$ (cm/sec) for $n_F = 0.40$		
	2.41	2.80	3.24	3.86	4.48	5.19
1.00E+00	-	-	-	-	-	-
1.00E+01	220.2	225.0	230.6	238.3	-	-
2.50E+01	202.1	204.0	206.2	209.3	212.4	216.0

Mean — Headwater Level (ft) for $v > v_{F,cr}$

k_h (cm/sec)	$v_{F,cr}$ (cm/sec) for $n_F = 0.25$			$v_{F,cr}$ (cm/sec) for $n_F = 0.40$		
		2.84			4.54	
1.20E+01		219.6			237.3	

Figure 36. Step 7 of Guidoux et al. worksheet: Critical headwater level for probabilistic analysis.

7. Brauns Method

Brauns (1985) proposed a relationship to estimate the critical Darcy velocity for initiation of soil contact erosion of sand below gravel as a function of median particle diameter of the sand, porosity of the gravel layer, and Darcy velocity of flow through the gravel layer. In Figure 37, the upper relationship is for a filter (gravel layer) porosity of 0.40, and the lower relationship is for a filter (gravel layer) porosity of 0.25.

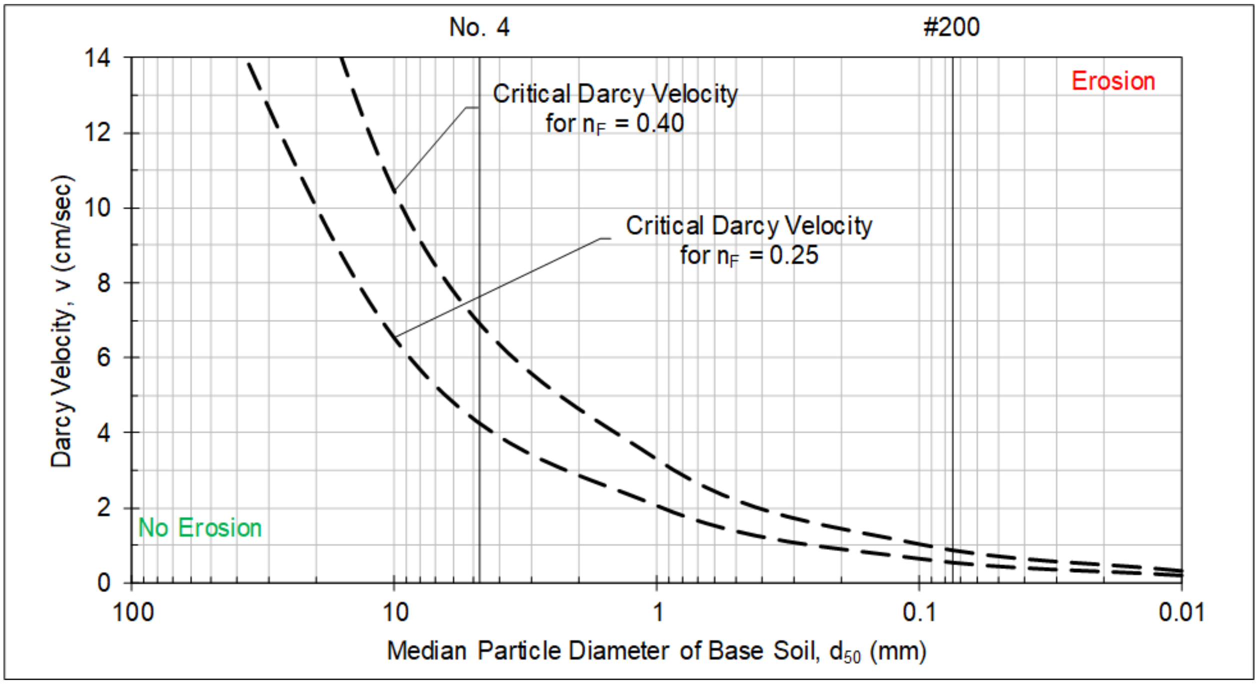


Figure 37. Critical Darcy velocity for sand below gravel for Brauns (1985) method.

7.1. Methods of Analysis

The method of analysis is the same as for the Guidoux et al. worksheet.

7.2. Base Soil Characterization

Step 2 characterizes the base soil. This input includes specific gravity of soil particles (G_s) and median particle diameter of the base soil (d_{50}). The median particle diameter of the base soil (d_{50}) is informed by the calculated values on the Gradation worksheet.

The selections in step 1 affect the input for step 2, and cells that do not apply have a gray background. These cells are not used in subsequent calculations even if data is present.

For deterministic analysis, input only the most likely value of d_{50}. The mean value used for subsequent calculations is the most likely (or mode) value. Figure 38 illustrates the deterministic input.

Step 2: Characterize the base soil (sand)

Specific gravity of sand particles, G_s 2.65

Parameter	Units	Minimum	Most Likely	Maximum
Median particle diameter, d_{50}	mm	9.764	11.440	13.403

Parameter	Units	Mean	@RISK Formula	Mean
d_{50}	mm	#NAME?		11.440

Figure 38. Step 2 of Brauns worksheet: Deterministic input.

For probabilistic analysis without using @RISK, input the minimum and maximum values in addition to the most likely value, and a triangular distribution represents d_{50}. The mean value used in subsequent calculations is the average of the minimum, most likely, and maximum values. Figure 39 illustrates the probabilistic input without using @RISK.

Step 2: Characterize the base soil (sand)

Specific gravity of sand particles, G_s 2.65

Parameter	Units	Minimum	Most Likely	Maximum
Median particle diameter, d_{50}	mm	9.764	11.440	13.403

Parameter	Units	Mean	@RISK Formula	Mean
d_{50}	mm	#NAME?		11.536

Figure 39. Step 2 of Brauns worksheet: Probabilistic input without using @RISK.

For probabilistic analysis using @RISK, input the minimum, most likely, and maximum values of d_{50}, and use an @RISK formula for a triangular distribution in the third column as a default. Alternatively, input a valid @RISK distribution in lieu of this default formula, and the user-specified input displays in the fourth column. The mean value used for subsequent calculations is the mean for the @RISK distribution entered in the third column. Figure 40 illustrates the probabilistic input using @RISK.

Step 2: Characterize the base soil (sand)

Specific gravity of sand particles, G_s 2.65

Parameter	Units	Minimum	Most Likely	Maximum
Median particle diameter, d_{50}	mm	9.764	11.440	13.403

Parameter	Units	Mean	@RISK Formula	Mean
d_{50}	mm	11.536	=@RiskTriang(F25,G25,H25)	11.536

Figure 40. Step 2 of Brauns worksheet: Probabilistic input using @RISK.

If using @RISK to perform probabilistic analysis, delete unnecessary calculation worksheets because the simulation is performed for all worksheets in the workbook, and this is time consuming. If cycling through iterations using @RISK, the displayed results are no longer mean values of the random variables; they are the selected iteration's values.

7.3. Filter (Gravel Layer) Characterization

The filter (gravel layer) characterization is the same as for the Guidoux et al. worksheet.

7.4. Critical Darcy Velocity for Initiation of Soil Contact Erosion

Step 4 calculates the critical Darcy velocity ($v_{F,cr}$) for initiation of soil contact erosion for sand below gravel as shown in Equation 8.

$$v_{F,cr}\ (m/s) = Fr_{cr} n_F \sqrt{\left(\frac{\rho_s - \rho_w}{\rho_w}\right) g\ d_{50}} \tag{8}$$

where:

Fr_{cr} = critical Froude number (0.65)
n_F = porosity of the filter (gravel layer)
ρ_s = density of the base soil particles (sand)
ρ_w = density of water
g = acceleration of gravity
d_{50} = median particle size of the base soil (sand)

Since it is easier to estimate the specific gravity of soil particles than the submerged density of soil particles, the following substitution is made to the equation for $v_{F,cr}$. as shown in Equation 9.

$$\frac{\rho_s - \rho_w}{\rho_w} = \frac{\rho_s'}{\rho_w} = G_s - 1 \tag{9}$$

where:

G_s = specific gravity of the base soil particles (sand)

Therefore, Equation 10 shows that the equation for $v_{F,cr}$ can be simplified to:

$$v_{F,cr}\ (m/s) = Fr_{cr} n_F \sqrt{(G_s - 1) g\ d_{50}} \tag{10}$$

Brauns (1985) showed that the critical Froude number is between 0.65 and 0.70 and recommended using the lower value of 0.65, which results in a lower critical Darcy velocity. Critical Darcy velocities are calculated for filter (gravel layer) porosities of 0.25 and 0.40, providing an upper and lower estimate as shown in Figure 41.

Step 4: Estimate the critical Darcy velocity for initiation of soil contact erosion

Critical Darcy velocity, $v_{F,cr}$ (m/sec) = $(Fr_{cr})(n_F)[(\rho_s'/\rho_w)(g)(D_{50}B)]^{0.5}$ where Fr_{cr} = critical Froude number

$v_{F,cr}$ (m/sec) = $0.65(n_F)[(G_s - 1)(g)(D_{50}B)]^{0.5}$	7.02	cm/sec for n_F = 0.25
using lower bound of range of Fr_{cr} from 0.65 to 0.70	11.24	cm/sec for n_F = 0.40

Figure 41. Step 4 of Brauns worksheet: Critical Darcy velocity.

7.5. Darcy Velocity of Flow in the Filter (Gravel Layer)

The Darcy velocity of flow in the filter (gravel layer) is the same as for the Guidoux et al. worksheet.

7.6. Likelihood of Initiation of Soil Contact Erosion

Step 6 compares the calculated Darcy velocity of flow in the filter (gravel layer) to the critical Darcy velocity for initiation of soil contact erosion. The equation for FS against initiation of soil contact erosion is the same as for the Guidoux et al. worksheet.

For deterministic analysis, the mean Darcy velocity of flow in the filter (gravel layer) is plotted as a function of headwater level and mean median particle diameter of the base soil (d_{50}). Reference lines for the critical Darcy velocity of flow through the filter (gravel layer) for porosities of 0.25 and 0.40 display as dashed lines. When a Darcy velocity at a given headwater level plots above the line of critical Darcy velocity based on the porosity of the filter (gravel layer), the FS is greater than 1, and initiation of soil contact erosion is not predicted. Figure 42 illustrates the graphical output of Darcy velocity for deterministic analysis.

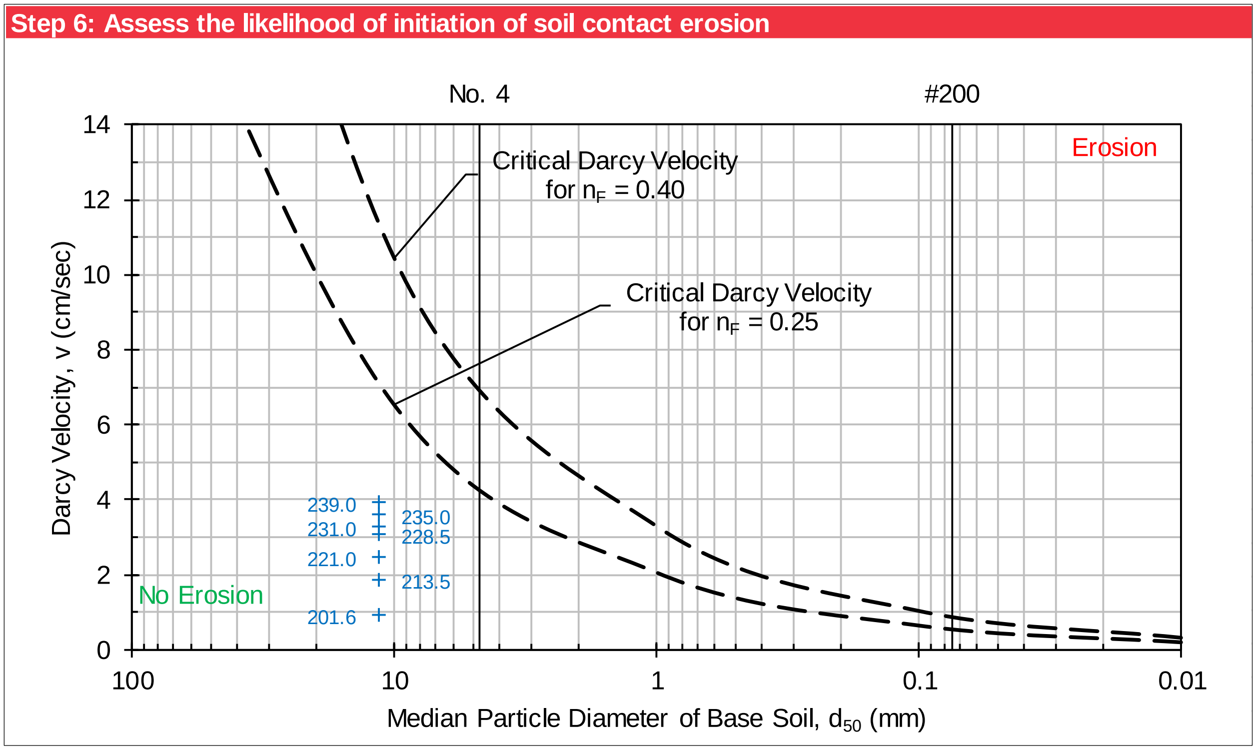


Figure 42. Step 6 of Brauns worksheet: Graphical output of Darcy velocity for deterministic analysis.

For probabilistic analysis, a black box is also plotted showing the distribution limits for median particle diameter of the base soil and Darcy velocity of flow in the filter (gravel layer). Reference lines for the critical Darcy velocity of flow through the filter (gravel layer) for porosities of 0.25 and 0.40 display as dashed lines. Initiation of soil contact erosion is predicted for median particle diameters and headwater combinations within the black box plotting above the line corresponding to the critical Darcy velocity being evaluated. Figure 43 illustrates the graphical output of Darcy velocity for probabilistic analysis. The two labels for critical Darcy velocity can be moved within the plot area as necessary for clarity.

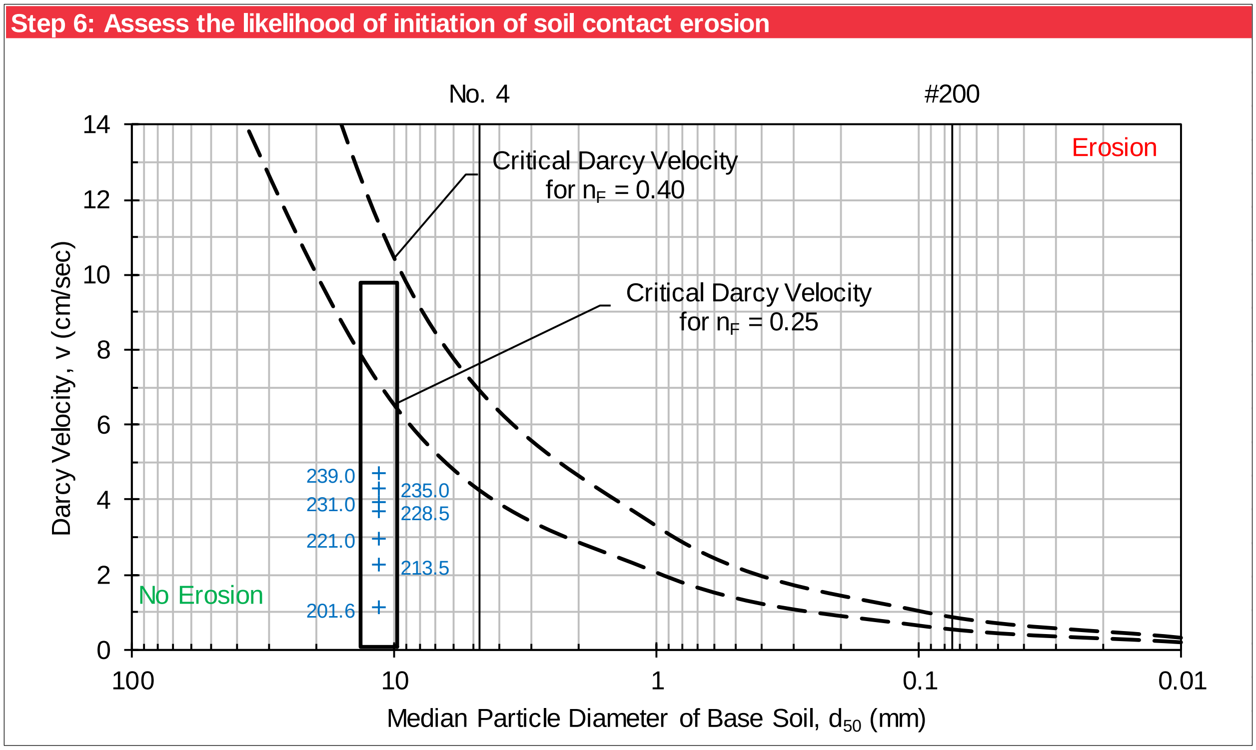


Figure 43. Step 6 of Brauns worksheet: Graphical output of Darcy velocity for probabilistic analysis.

Figure 44 illustrates the plot options for this chart. The maximum value for the y-axis (velocity) and minimum and maximum values for the x-axis (median particle diameter of the base soil) are user-specified.

Worksheet	Brauns		
y-axis bounds			
minimum	0		Value Primary Min: 0
maximum	14.0	◄ Enter maximum velocity.	Value Primary Max: 14
x-axis bounds			
minimum	0.010	◄ Enter minimum median diameter.	Category Primary Min: 0.01
maximum	100	◄ Enter maximum median diameter.	Category Primary Max: 100

Figure 44. Step 6 of Brauns worksheet: Plot options of Darcy velocity for graphical output.

The remainder of this step is the same as for the Guidoux et al. worksheet.

7.7. Headwater Level for Initiation of Soil Contact Erosion

The headwater level for initiation of soil contact erosion is the same as for the Guidoux et al. worksheet.

8. References

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Appendix A. Acronym List

CPD	Computer Program Document
FS	Factor of Safety
HEC	Hydrologic Engineering Center
HW	Headwater
IWR	Institute for Water Resources
NAVD 88	North American Vertical Datum of 1988
NGVD 29	National Geodetic Vertical Datum of 1929
QC	Quality Control
RMC	Risk Management Center
UDF	User-Defined Function
U.S.	United States
USACE	United States Army Corps of Engineers