RMC Internal Instability Toolbox

RMC Internal Erosion Suite

RMC-CPD-2023-10

November 2023

US Army Corps
of Engineers®
Dam and Levee Safety Programs

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Cover Photo: Coarse portion of soils from the W.A.C. Bennett Dam; Li, M. (2008). *Seepage-induced instability in widely graded soils*. [Doctoral dissertation, Department of Civil Engineering, University of British Columbia]. https://doi.org/10.14288/1.0063080.

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Prepared by the Risk Management Center

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14. ABSTRACT
The spreadsheet tools contained in the toolbox deterministically assess the susceptibility to internal instability using the Burenkova (1993) method, modified Burenkova method of Wan and Fell (2004), alternative method of Wan and Fell (2008), modified Kenney and Lau method of Li and Fannin (2008), and suggested method for classifying mechanism and amount of internal erosion of Douglas et al. (2019).

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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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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 Internal Instability 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.

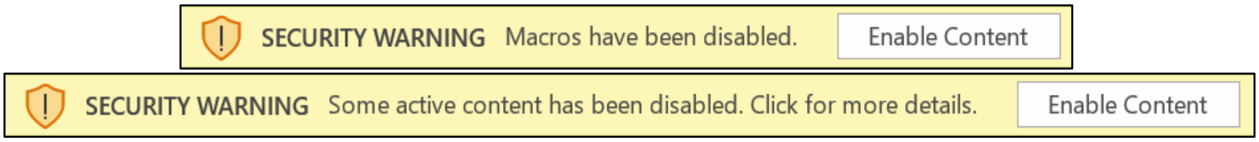


Figure 1. Security warning message bars with the “Enable Content” option to enable macros.

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

Internal instability describes the susceptibility of a soil to seepage-induced movement and loss of fine particles in the soil matrix. Various terms have been used in technical literature and research to describe the internal erosion mechanism associated with internally unstable soils, often inconsistently.

Suffusion is defined as selective erosion of finer particles from the matrix of coarser particles (that are in point-to-point contact) of an internally unstable soil such that the finer particles are removed through the voids between the coarser particles by seepage flow, leaving behind a soil skeleton formed by the coarser particles. The voids are underfilled such that the volume of finer particles fits within the voids formed by the coarser particles. Therefore, effective stresses do not load the finer particles. The seepage-induced mass loss results in little or no change in volume and an increase in hydraulic conductivity particles as illustrated in Figure 8 (Fannin and Slangen 2014).

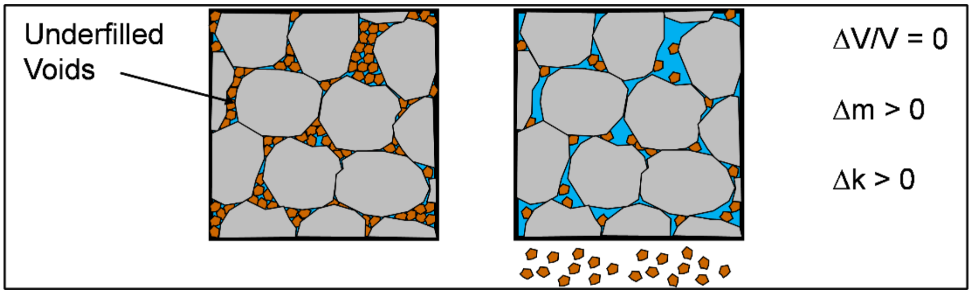


Figure 8. Suffusion (after Fannin and Slangen 2014).

Suffosion is a similar process. However, the voids are overfilled such that the coarser particles float within the finer particles, and effective stresses load the finer particles. The seepage-induced mass loss results in a reduction in volume and a change in hydraulic conductivity particles as illustrated in Figure 9. Suffosion is less likely under the stress conditions and gradients typically found in embankment dams.

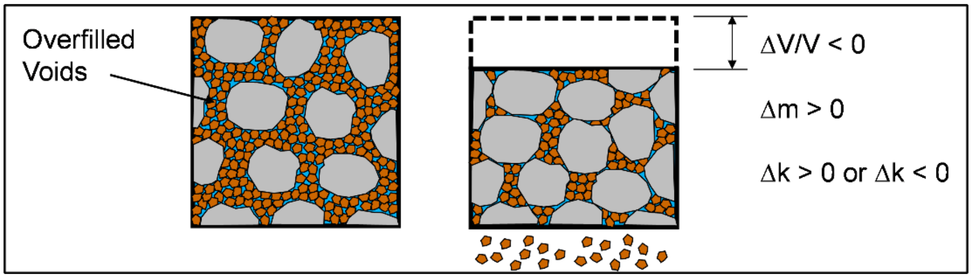


Figure 9. Suffosion (after Fannin and Slangen 2014).

Both processes associated with internally unstable soils are secondary or contributing mechanisms that can lead to one of the primary mechanisms of internal erosion.

Several methods have been proposed to assess susceptibility to internal instability based on particle-size analysis. This toolbox assesses the geometric condition for initiation (susceptibility to internal instability) for the following methods:

- Burenkova (1993) method

- Modified Burenkova method for broadly graded and gap-graded soils (Wan and Fell 2004)
- Alternative method for broadly graded soils (Wan and Fell 2008)
- Modified Kenney and Lau method for broadly graded and gap-graded soils (Li and Fannin 2008)

It also includes the suggested method for mechanism and amount of erosion for broadly graded soils of Douglas et al. (2019).

Correctly applying these methods requires understanding the context from which each method was developed as described in the following sections. These methods, along with sensitivity analysis, can be used as the first step to estimate the susceptibility to internal instability. If, by using such methods, the soil is clearly not susceptible to internal instability and erosion of fine particles, it is unlikely that further effort is necessary. However, if such methods lead to uncertainty, laboratory tests should be conducted on actual soil gradations that carefully simulate the field conditions.

5. Gradation

This worksheet analyzes particle sizes of the soil being evaluated for susceptibility to internal instability. The particle-size analysis is performed according to the Unified Soil Classification System (USCS) per American Society for Testing and Materials (ASTM) D2487.

The input includes sieve size (inches or sieve number), particle size (millimeters) for hydrometer analysis, and percent finer (by weight).

Use the drop-down list to select the sieve sizes that define soil gradation. Coarse sieve designations range from 12 inches to 0.25 inches, and standard sieve designations range from No. 4 to No. 200. The particle size (*D*) in millimeters automatically populates with a sieve size selection. If a hydrometer (sedimentation) analysis was performed on the fine-grained portion of the soil (passing the No. 200 sieve), select "Hydrometer" from the drop-down list for sieve size and input particle sizes. Particle sizes from sieve or hydrometer analysis must be in descending order.

The user-specified percent finer (by weight) for the 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. The input must be a decimal number, consisting of a whole number and a fractional part (for example, 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 is an example of gradation input.

Classification of Coarse-Grained Soils
Unified Soil Classification System (ASTM D2487)

Sieve Size	D (mm)		F (percent)
	Sieve	Hydrometer	
3-in	75		100.0
1-in	25		54.0
3/4-in	19		46.4
1/2-in	12.5		39.8
3/8-in	9.5		37.0
No. 4	4.75		29.7
No. 10	2		24.5
No. 16	1.18		22.0
No. 20	0.85		20.0
No. 30	0.6		18.0
No. 40	0.425		16.0
No. 50	0.3		14.5
No. 70	0.212		13.0
No. 100	0.15		11.5
No. 140	0.106		11.0
No. 200	0.075		9.5
Hydrometer	-	0.05	8.0
Hydrometer	-	0.01	2.7
Hydrometer	-	0.005	1.3
Hydrometer	-	0.001	0.0

Figure 10. Gradation worksheet: Gradation input.

A particle-size plot is generated from the user-specified input with particle size (millimeters) on the x-axis and percent finer by weight on the y-axis. In Figure 11, 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.

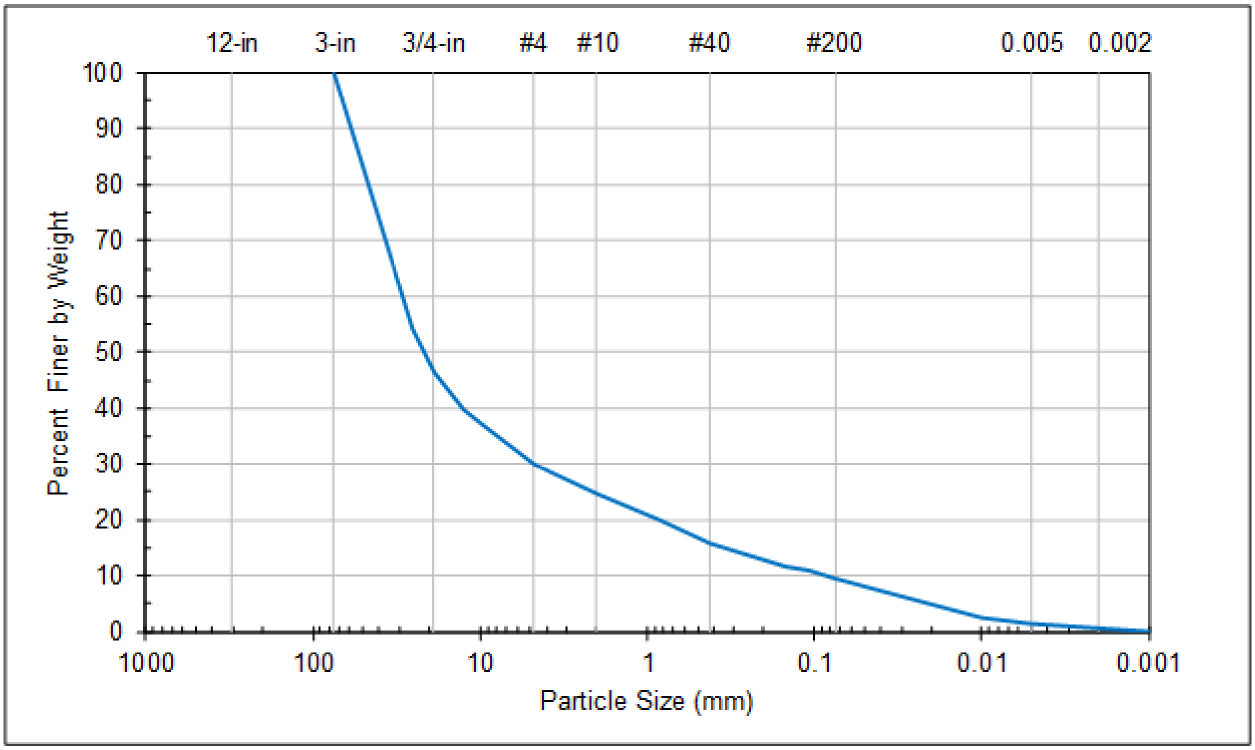


Figure 11. Gradation worksheet: Particle size plot.

The end of the worksheet summarizes the particle-size analysis for the user-specified gradation, as illustrated in Figure 12 and Figure 13. The boulder percentage (larger than 12-inch sieve), cobble percentage (passing 12-inch sieve and retained on 3-inch sieve), gravel percentage (including coarse and fine gravel), sand percentage (including coarse, medium, and fine sand), and fines content (*FC*) (including estimated silt and clay percentages) are calculated. If 12 percent or less of the soil passes the No. 200 sieve, the D_{60}, D_{30}, D_{10}, coefficient of uniformity (C_u), and coefficient of curvature (C_c) are calculated per ASTM D2487, as illustrated in Figure 12. If greater than 12 percent of the soil passes the No. 200 sieve, these calculations are not performed, and cells that do not apply have a gray background, as illustrated in Figure 13.

Equation 1 calculates the coefficient of uniformity.

$$C_u = \frac{D_{60}}{D_{10}} \quad (1)$$

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

Equation 2 calculates the coefficient of curvature.

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

where:

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

Boulder, larger than 12-in sieve	0.0	percent
Cobble, passing 12-in sieve and retained on 3-in sieve	0.0	percent
Gravel, passing 3-in sieve and retained on No. 4 sieve	70.3	percent
Coarse gravel, passing 3-in sieve and retained on ¾-in sieve	53.6	percent
Fine gravel, passing ¾-in sieve and retained on No. 4 sieve	16.7	percent
Sand, passing No. 4 sieve and retained on No. 200 sieve	20.2	percent
Coarse sand, passing No. 4 sieve and retained on No. 10 sieve	5.2	percent
Medium sand, passing No. 10 sieve and retained on No. 40 sieve	8.5	percent
Fine sand, passing No. 40 sieve and retained on No. 200 sieve	6.5	percent
Silt and clay, passing No. 200 sieve	9.5	percent

Calculate the following only if 12 percent or less passes the No. 200 sieve:

D_{60}	28.852	mm	Coefficient of uniformity, $C_u = D_{60} / D_{10}$	342.8
D_{30}	4.866	mm	Coefficient of curvature, $C_c = (D_{30})^2 / D_{10} / D_{60}$	9.8
D_{10}	0.084	mm		

Figure 12. Gradation worksheet: Particle-size analysis with 12 percent or less passing No. 200 sieve.

Boulder, larger than 12-in sieve	0.0	percent
Cobble, passing 12-in sieve and retained on 3-in sieve	0.0	percent
Gravel, passing 3-in sieve and retained on No. 4 sieve	60.0	percent
Coarse gravel, passing 3-in sieve and retained on ¾-in sieve	30.0	percent
Fine gravel, passing ¾-in sieve and retained on No. 4 sieve	30.0	percent
Sand, passing No. 4 sieve and retained on No. 200 sieve	27.0	percent
Coarse sand, passing No. 4 sieve and retained on No. 10 sieve	10.0	percent
Medium sand, passing No. 10 sieve and retained on No. 40 sieve	12.0	percent
Fine sand, passing No. 40 sieve and retained on No. 200 sieve	5.0	percent
Silt and clay, passing No. 200 sieve	13.0	percent

Calculate the following only if 12 percent or less passes the No. 200 sieve:

D_{60}	#N/A	mm	Coefficient of uniformity, $C_u = D_{60} / D_{10}$	#N/A
D_{30}	#N/A	mm	Coefficient of curvature, $C_c = (D_{30})^2 / D_{10} / D_{60}$	#N/A
D_{10}	#N/A	mm		

Figure 13. Gradation worksheet: Particle-size analysis with greater than 12 percent passing No. 200 sieve.

Following the particle-size analysis, characterize the fines using the results of Atterberg limits testing (ASTM D4318) or visual-manual fines classification (ASTM D2488). Use the drop-down list to specify if Atterberg limits testing was performed on the fines.

- If Yes, the liquid limit (*LL*), plastic limit (*PL*), and liquid limit (oven-dried) are user-specified input, as illustrated in Figure 14. Calculate the plasticity index (*PI*) as *LL* – *PL*. If the results of Atterberg limits testing show the fines are non-plastic, enter a value of *NP* for the *PL*, as illustrated in Figure 15.

- If No, use the drop-down list to specify the visual-manual fines classification according to ASTM D2488. Three options are available for soil classification using visual-manual procedures: *ML* or *MH*, *CL-ML*, and *CL* or *CH*. Cells that do not apply have a gray background, as illustrated in Figure 14 through Figure 16.

Was Atterberg limits testing (ASTM D4318) performed on the fines?			Yes
Liquid limit, LL	35	Plasticity index, PI	12
Plastic limit, PL	23	Liquid limit (oven-dried)	
Visual-manual classification of fines (ASTM D2488)			CL or CH

Figure 14. Gradation worksheet: Fines classification using Atterberg limits for plastic fines.

Was Atterberg limits testing (ASTM D4318) performed on the fines?			Yes
Liquid limit, LL	35	Plasticity index, PI	NP
Plastic limit, PL	NP	Liquid limit (oven-dried)	
Visual-manual classification of fines (ASTM D2488)			CL or CH

Figure 15. Gradation worksheet: Fines classification using Atterberg limits for non-plastic fines.

Was Atterberg limits testing (ASTM D4318) performed on the fines?			No
Liquid limit, LL		Plasticity index, PI	
Plastic limit, PL		Liquid limit (oven-dried)	
Visual-manual classification of fines (ASTM D2488)			CL or CH

Figure 16. Gradation worksheet: Fines classification using visual-manual procedures.

Figure 17 illustrates the soil classification according to the USCS, and the group symbol, corresponding group name, and abbreviated soil classification symbol are provided. More information about the particle size range of the sand (based on the calculated fine, medium, and coarse sand contents) and gravel particles (based on calculated fine and coarse gravel contents) is also provided under Sand Subdivisions and Gravel Subdivisions, respectively.

Group Symbol	GP	Abbreviated Soil Classification Symbol	(GP)s
Group Name	poorly graded gravel with sand		
Sand Subdivisions	fine to coarse sand		
Gravel Subdivisions	fine to coarse gravel		

Figure 17. Gradation worksheet: Soil classification.

6. Screening

This worksheet provides general characteristics to initially screen a soil's susceptibility to internal instability based on the shape of the gradation curve.

6.1. Coarse, Broadly Graded Soils Typically of Glacial Origin

In self-filtering soils, the coarse particles prevent the internal erosion of the medium particles, and the medium particles prevent internal erosion of the fine particles. Soils which potentially do not self-filter are also susceptible to internal instability.

According to Sherard (1979), soils are generally considered internally unstable if the coarser fraction of the material does not filter the finer fraction. Sherard obtained data from a number of embankment dams where sinkholes appeared on the crest and slopes of widely graded embankments of glacial origin and plotted a band around these gradations. The internally unstable soil gradations usually plotted as nearly straight lines or slight curves. The soils have a volume of fine particles greater than the volume of voids between the coarse sand and gravel fraction, and the coarser particles float in the finer particles.

As the example in Figure 18 illustrates, the user-specified gradation from the Gradation worksheet is plotted against Sherard's unstable band for screening these characteristics.

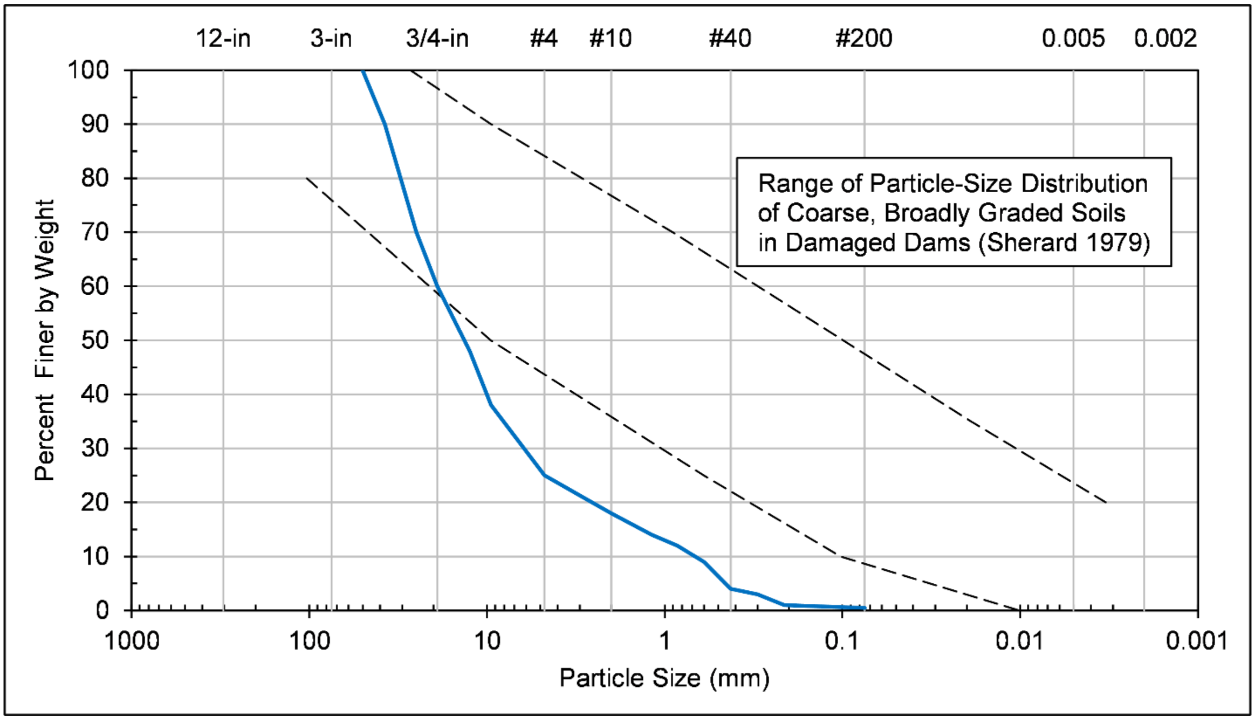


Figure 18. Screening worksheet: Broadly graded soils with poor self-filtering characteristics (Sherard 1979).

6.2. Broadly Graded Soils with a Flat Tail of Fines and Gap-Graded Soils

Figure 19 illustrates the two examples from Fell et al. (2008) of gradations susceptible to internal instability: a broadly graded soil with a flat tail of fines and a gap-graded soil. Broadly graded soil has a wide range of particle sizes (e.g., cobbles and gravels with sands, clays, and silts) with excessive fines that plot as a flat tail on the gradation curve. Gap-graded soil has a broad gradation in which a distinct portion (range of particle sizes) is significantly under-represented or completely absent. As illustrated, the finer fraction is the point of inflection for broadly graded soils and the fine limit of the gap for gap-graded soils.

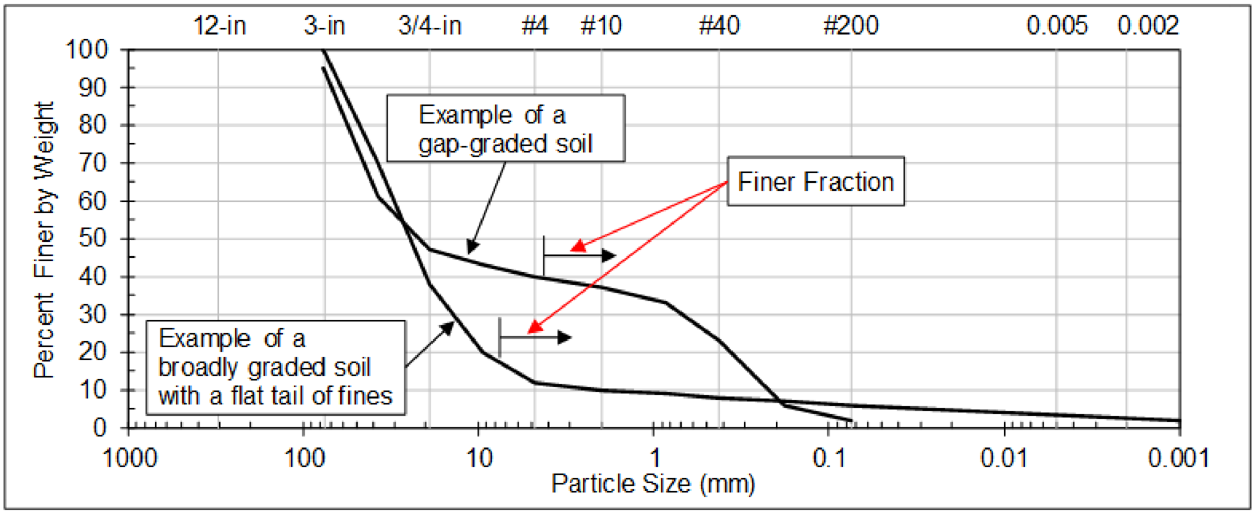


Figure 19. Screening worksheet: Examples of internally unstable soil gradations (adapted from Fell et al. 2008).

7. Burenkova Method

Based on three representative soil fractions (D_{90}, D_{60}, and D_{15}), Burenkova (1993) characterized the heterogeneity of cohesionless sand-gravel soils, with maximum particle sizes up to 100 millimeters and coefficients of uniformity up to 200, using two conditional factors of uniformity (h' and h''), as shown in Equations 3 and 4.

$$h' = \frac{D_{90}}{D_{60}} \tag{3}$$

$$h'' = \frac{D_{90}}{D_{10}} \tag{4}$$

where D_{90}, D_{60}, and D_{15} are the particle sizes corresponding to 90, 60, and 15 percent finer by weight on the cumulative particle-size distribution curve, respectively.

According to Wan and Fell (2008), the value of h' represents the slope of the coarse part of the particle-size distribution plot, with high values of h' representing near single-size coarse particles having large constriction spaces compared to a well-graded soil. The value of h'' is a measure of the filter action between the coarse fraction and the finer fraction.

Figure 20 illustrates laboratory test results plotted on a semi-logarithmic diagram and divided into four zones, with Zones I and III representing zones of suffusive soils, Zone II representing a zone of non-suffusive soils, and Zone IV representing a zone of artificial soils. The domain of the Zone II (non-suffusive soils) was approximated by the following inequalities defining the Zone II boundaries, as shown in Equation 5.

$$0.76\log(h'') + 1 < h' < 1.86\log(h'') + 1 \tag{5}$$

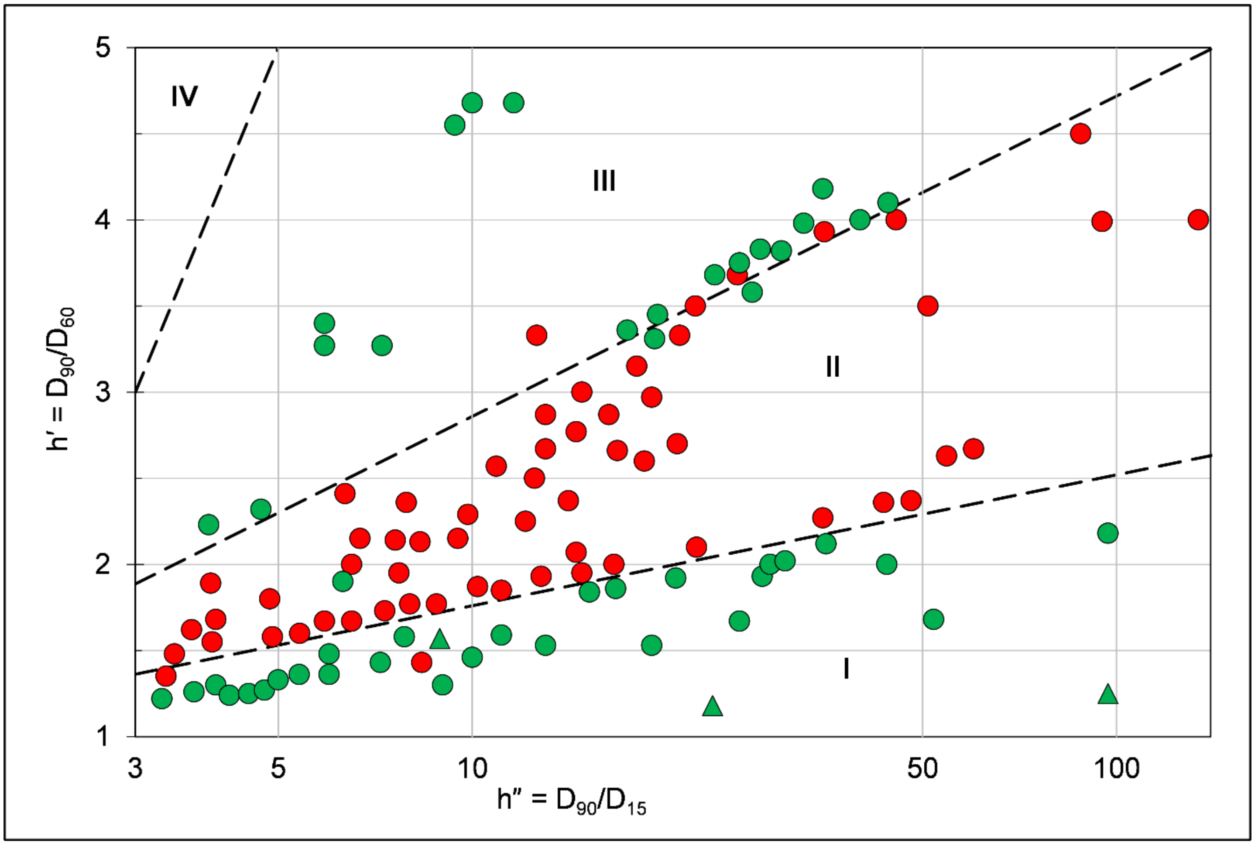


Figure 20. Soils susceptible to internal instability (adapted from Burenkova 1993).

Based on the particle-size analysis on the Gradation worksheet, D_{90}, D_{60}, and D_{15} are interpolated using logarithmic scale for particle size and linear scale for percent finer by weight to calculate the values of h' and h''. Figure 21 illustrates an example of the particle-size analysis.

D_{90}	37.500	mm	$h' = D_{90}/D_{60}$	1.974
D_{60}	19.000	mm	$h'' = D_{90}/D_{15}$	27.852
D_{15}	1.346	mm		

Figure 21. Burenkova Method worksheet: Particle-size analysis.

The results are plotted at the end of the worksheet. Figure 22 illustrates an example of the output. The Zone II boundaries are plotted as black dashed lines. Red text indicates the suffusive Zones I and III, and green text indicates the non-suffusive Zone II. The evaluated soil is plotted as a blue dot.

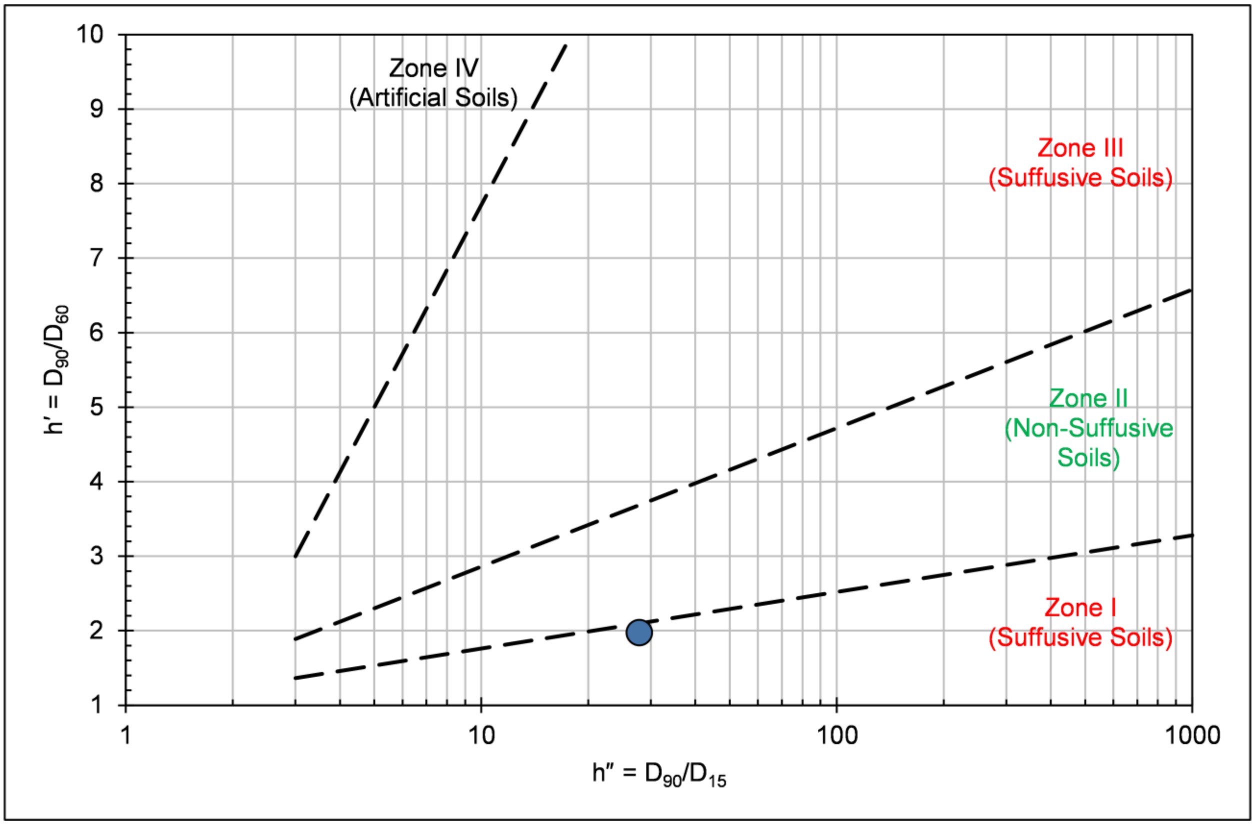


Figure 22. Burenkova Method worksheet: Graphical output.

Figure 23 shows the plot options for Figure 22. The maximum values for the x-axis (*h″*) and y-axis (*h′*) are user-specified.

Worksheet	Burenkova Method		
y-axis bounds			
minimum	1		Value Primary Min: 1
maximum	10	◄ Enter maximum h′ .	Value Primary Max: 10
x-axis bounds			
minimum	1		Category Primary Min: 1
maximum	1,000	◄ Enter maximum h″.	Category Primary Max: 1000

Figure 23. Burenkova Method worksheet: Plot options.

8. Modified Burenkova Method

The Burenkova (1993) method characterized the heterogeneity of cohesionless sand-gravel soils using two conditional factors of uniformity: h' and h'', where D_{90}, D_{60}, and D_{15} are the particle sizes corresponding to 90, 60, and 15 percent finer by weight on the cumulative particle-size distribution curve, respectively.

Wan and Fell (2008) indicated that the Burenkova (1993) method does not provide a clear boundary between internally stable and unstable soils. As illustrated in Figure 24 and Figure 25, they performed logistic regression to define contours of equal probability of internal instability as a function of h' and h'' for silt-sand-gravel and clay-silt-sand-gravel soils of limited clay content and plasticity and sand-gravel soils with less than 10 percent non-plastic fines.

Equation 6 defines the probability contours of internally unstable soils (P_{IUS}) or the probability of internal instability (P_{IUS}) from the logistic regression.

$$P_{IUS} = \frac{e^Z}{1 + e^Z} \tag{6}$$

where:

$$Z = 2.378 \log(h'') - 3.648h' + 3.701 \tag{7}$$

for silt-sand-gravel soils and clay-silt-sand-gravel soils of limited clay content and plasticity, and:

$$Z = 3.875 \log(h'') - 3.591h' + 2.436 \tag{8}$$

for sand-gravel soils with less than or equal to 10 percent non-plastic fines.

Figure 25 illustrates Burenkova (1993) had a second zone (Zone III) of suffusive soils. Wan and Fell (2004) did not test soils in this range. These soils have a concave downward shape, and they indicated such soils are uncommon and are expected to be internally stable.

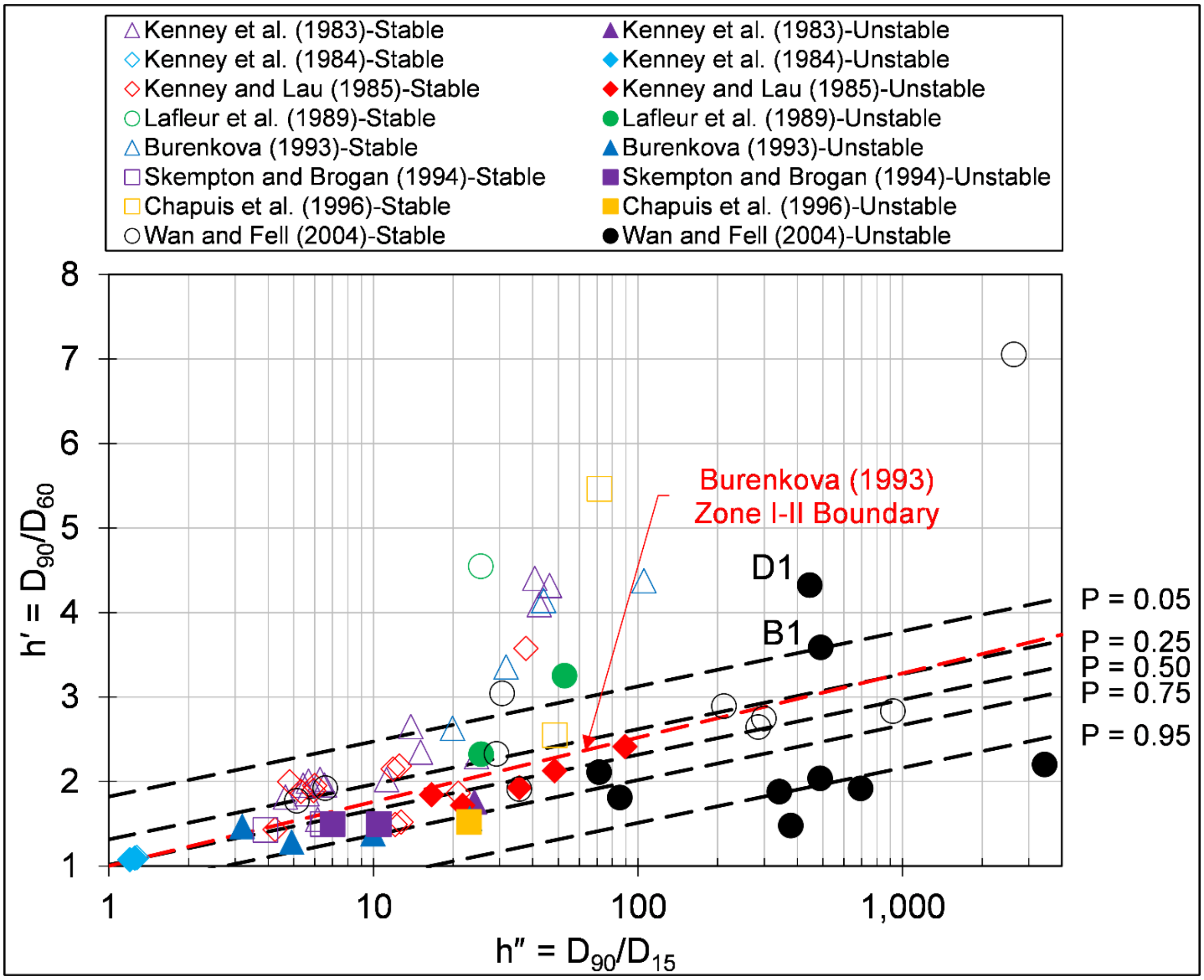


Figure 24. Probability of internal instability for silt-sand-gravel soil and clay-silt-sand-gravel soils of limited clay content and plasticity (after Wan and Fell 2004).

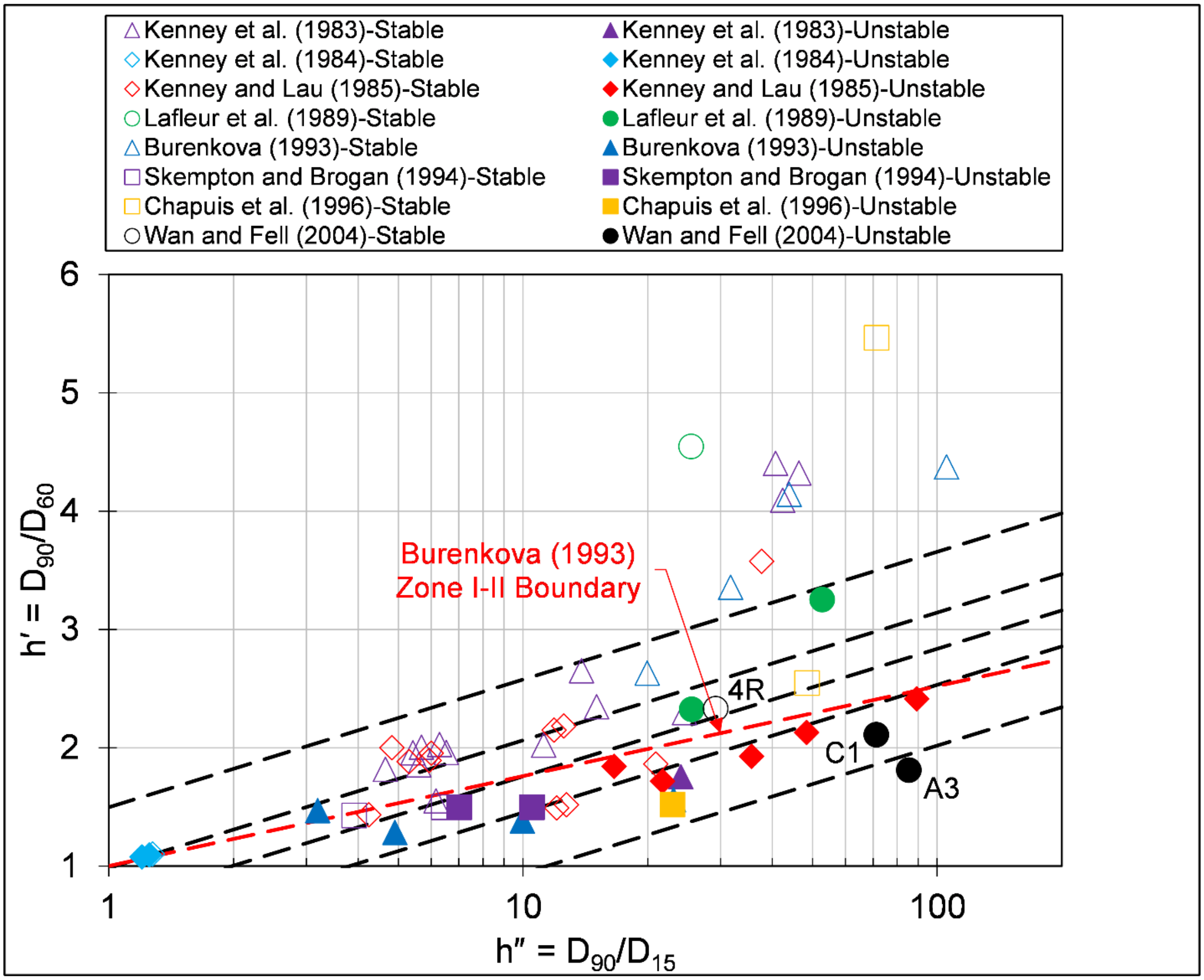


Figure 25. Probability of internal instability for sand-gravel soils with less than 10 percent non-plastic fines (after Wan and Fell 2004).

This worksheet assesses the susceptibility of broadly graded and gap-graded soils using the modified Burenkova method of Wan and Fell (2008). Soils having a finer fraction of less than 15 percent may not be adequately assessed by this method.

Calculating *h′* and *h″* is the same as the Burenkova Method worksheet. Two options, discussed in sections 8.1 and 8.2, are provided, depending on the applicable soil classification.

8.1. Silt-Sand-Gravel Soils and Clay-Silt-Sand-Gravel Soils

Option 1 evaluates silt-sand-gravel soils and clay-silt-sand-gravel soils of clay-size fraction (*CF*, finer than 0.002 millimeter) less than or equal to 10 percent and *PI* less than or equal to 12. Based on the particle-size analysis on the Gradation worksheet, the *CF* is interpolated using logarithmic scale for particle size (0.002 millimeter) and linear scale for percent finer by weight. The soil classification is also obtained from the Gradation worksheet. If Atterberg fines limits testing was performed, the *PI* is obtained from the Gradation worksheet. If Atterberg fines limits testing was not performed, the *PI* has a gray background.

Equation 9 estimates the probability of internal instability (P_{IUS}) by combining Equations 6 and 7.

$$P_{IUS} = \frac{1}{1 + e^{-(2.378 \log(h'') - 3.648h' + 3.701)}} \tag{9}$$

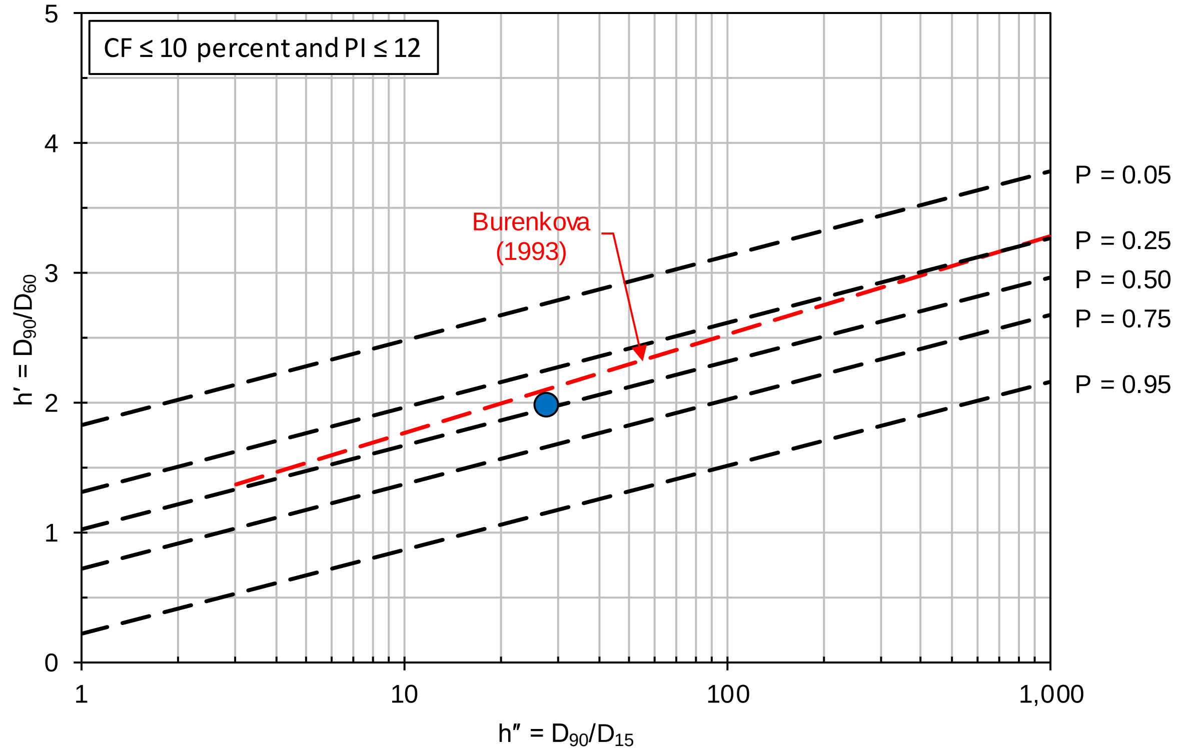
Figure 26 is an example of the output. Five logistic regression lines of probability are plotted as dashed black lines for reference (5, 25, 50, 75, and 95 percent probability of internal instability) and the soil being evaluated is plotted as a blue dot. The Burenkova (1993) Zone I boundary for suffusive soils is plotted as a red dashed line for reference.

If the *CF* is greater than 10 percent or the *PI* is greater than 12, values that do not meet the criteria for the method have an orange background. If the *CF* cannot be interpolated or Atterberg limits testing of the fines was not performed, use judgment to determine whether the soil is of limited clay content and plasticity.

The soil being evaluated is plotted even if one or more criteria is not met or not calculated on the Gradation worksheet. Therefore, use judgment to determine if Option 1 is applicable.

Option 1: Silt-sand-gravel soils and clay-silt-sand-gravel soils of limited clay content and plasticity

Clay-size fraction (< 0.002 mm), CF	#N/A	percent
Plasticity index of fines, PI	#N/A	



$Z = 2.378 \cdot \log(h'') - 3.648(h') + 3.701$	-6.31E-02
Probability of internally unstable soils, $P_{IUS} = e^Z / (1 + e^Z)$	4.84E-01

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 26. Option 1 of Modified Burenkova Method worksheet: Graphical output.

The plot options are the same as the Burenkova Method worksheet.

8.2. Sand-Gravel Soils

Option 2 evaluates sand-gravel soils with less than 10 percent non-plastic fines (*FC*, percentage finer than 0.075 millimeter). Based on the particle-size analysis on the Gradation worksheet, the *FC* is interpolated using logarithmic scale for particle size (0.075 millimeter) and linear scale for percent finer by weight. The soil classification is also obtained from the Gradation worksheet. If Atterberg limits testing of the fines was performed, the *PL* is obtained from the Gradation worksheet. If Atterberg limits testing of the fines was not performed, the *PL* has a gray background.

Equation 10 combines Equations 6 and 8 to estimate the probability of internal instability (P_{IUS}).

$$P_{IUS} = \frac{1}{1 + e^{-(3.875\log(h'') = 3.591h' + 2.436)}} \tag{10}$$

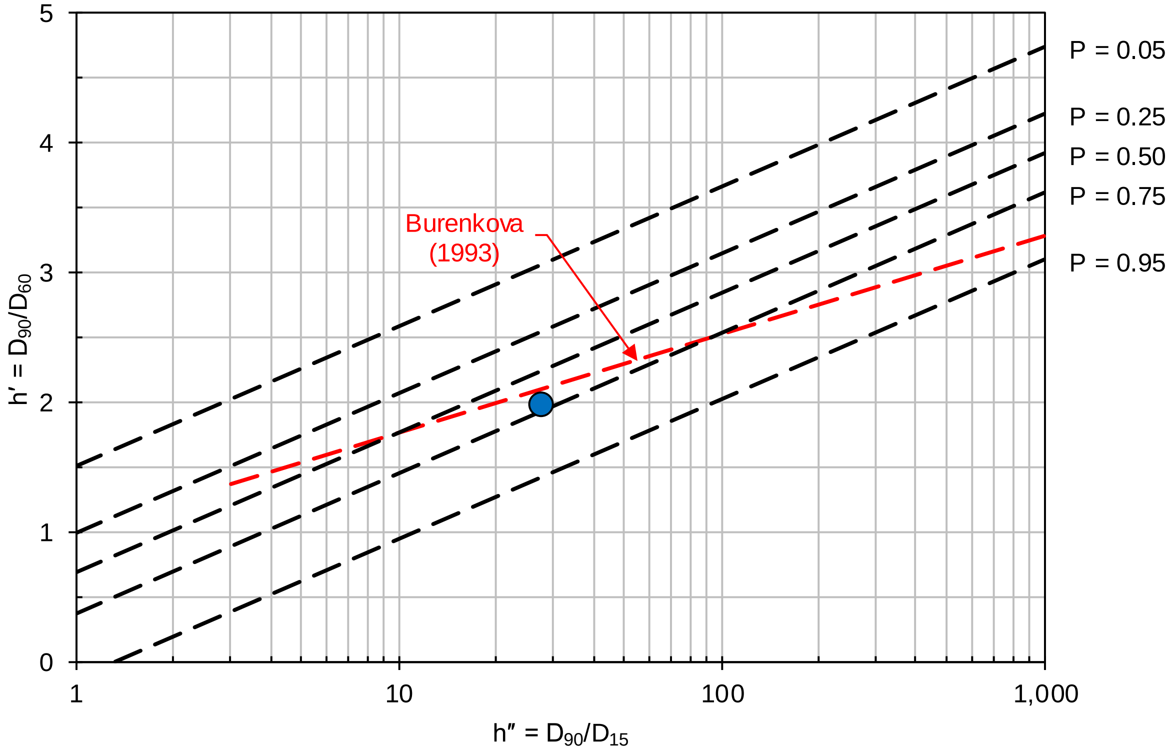
Figure 27 is an example of the output. Five logistic regression lines of probability are plotted as dashed black lines for reference (5, 25, 50, 75, and 95 percent probability of internal instability), and the soil being evaluated is plotted as a blue dot. The Burenkova (1993) Zone I boundary for suffusive soils is plotted as a red dashed line for reference.

If the *FC* is greater than 10 percent or the *PL* is not NP, values that do not meet the criteria for the method have an orange background. If the *FC* cannot be interpolated or Atterberg limits testing was not performed, use judgement to determine whether the soil has limited non-plastic fines.

The soil being evaluated is plotted even if one or more criteria is not met or not calculated on the Gradation worksheet, so use judgement to determine if Option 2 applies.

Option 2: Sand-gravel soils with less than or equal to 10 percent non-plastic fines

Fines content, FC	0.5	percent
Plastic limit of fines, PL	#N/A	



$Z = 3.875 \cdot \log(h'') - 3.591(h') + 2.436$	9.47E-01
Probability of internally unstable soils, $P_{IUS} = e^Z / (1 + e^Z)$	7.21E-01

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 27. Option 2 of Modified Burenkova Method worksheet: Graphical output.

The plot options are the same as the Burenkova Method worksheet.

9. Alternative Method

Wan and Fell (2008) determined that the methods of Kenney and Lau (1985, 1986) or Sherard (1979) were too conservative for silt-sand-gravel and clay-silt-sand-gravel soils. Based on their experience with the modified Burenkova method, soils with a steep slope on the coarse fraction and a flat slope on the finer fraction were likely internally unstable. They developed an alternative method for broadly graded silt-sand-gravel soils using the ratios of D_{90}/D_{60} and D_{20}/D_5, where D_{90}, D_{60}, D_{20}, and D_5 are the particle sizes corresponding to 90, 60, 20, and 5 percent finer by weight on the cumulative particle-size distribution curve, respectively.

Wan and Fell (2008) identified two boundaries related to internal instability, as illustrated in Figure 28. The first is associated with a low likelihood of internal instability (or stable zone), and the second is associated with a very high likelihood of internal instability (or unstable zone). A transition zone is between these two zones where both stable and unstable soil gradations were observed.

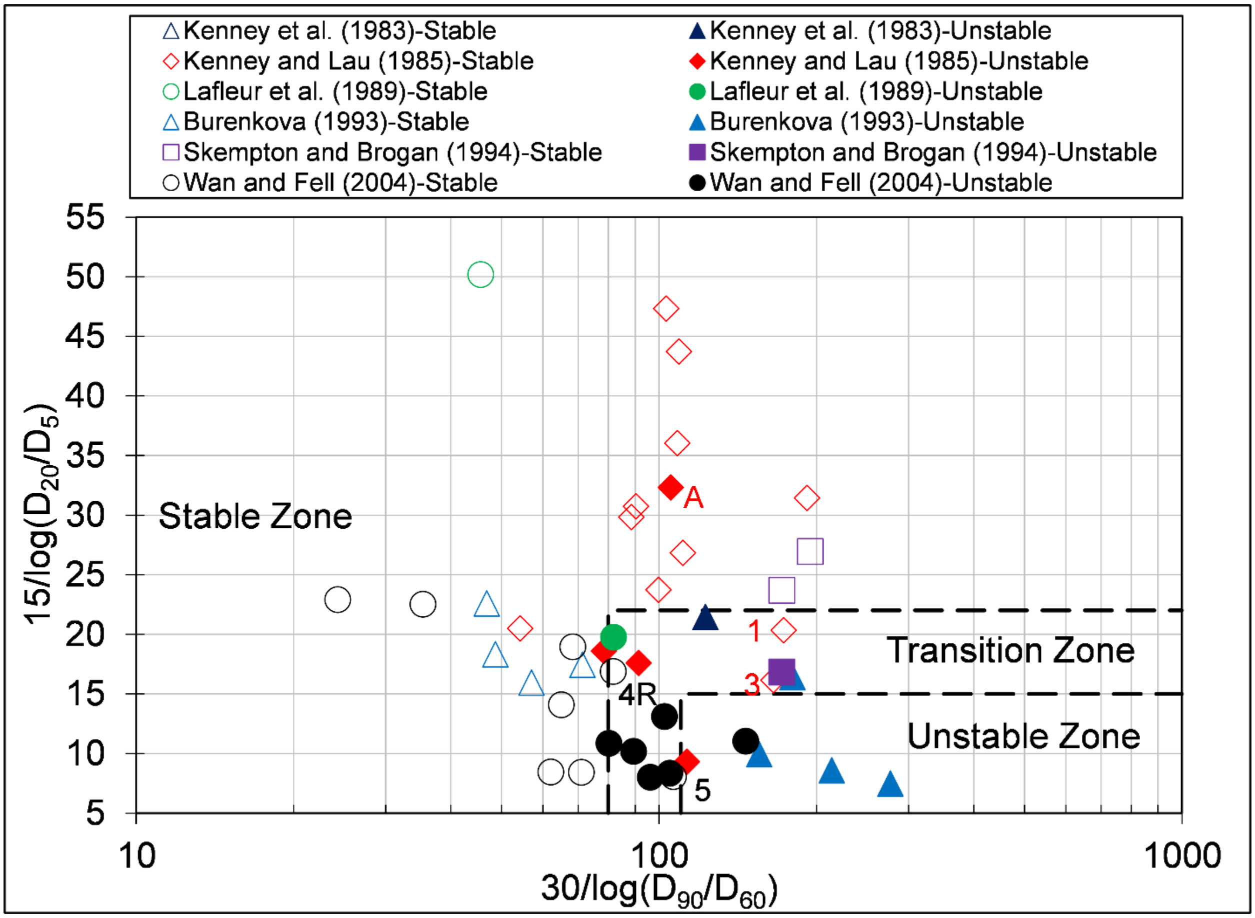


Figure 28. Alternative method for assessing internal instability of broadly graded silt-sand-gravel soils (adapted Wan and Fell 2008).

9.1. Applicability

This worksheet assesses the susceptibility of broadly graded silt-sand-gravel soils to internal instability using the Wan and Fell (2008) alternative method. This method is not applicable to gap-graded soils, and soils that have a finer fraction less than 20 percent may not be adequately assessed by this method. While it has not been proven by tests, Wan and Fell (2008) indicated if the slope of the finer fraction is used in lieu of the D_{20}/D_5 ratio, the method should be applicable.

In step 1, the user-specified gradation from the Gradation worksheet is plotted as a black line against the stable gradations (green lines) and unstable gradations (red lines) used to develop the method for visual comparison, as illustrated in Figure 29.

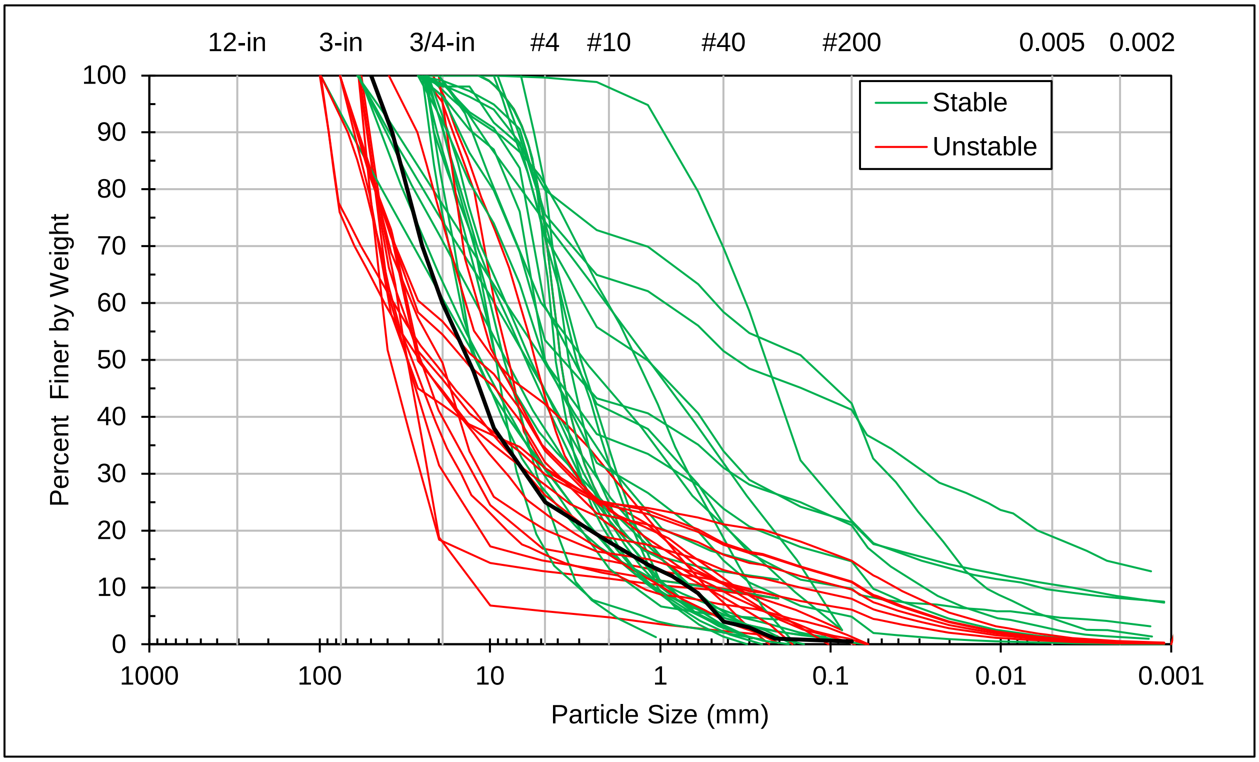


Figure 29. Step 1 of Alternative Method worksheet: Gradation comparison.

9.2. Susceptibility to Internal Instability

In step 2, the susceptibility to internal instability of the user-specified gradation is assessed. Based on the particle-size analysis on the Gradation worksheet, D_{90}, D_{60}, D_{20}, and D_5 are interpolated using logarithmic scale for particle size and linear scale for percent finer by weight to calculate the x-axis value [$30/\log(D_{90}/D_{60})$] and y-axis value [$15/\log(D_{20}/D_5)$].

Figure 30 is an example of the particle-size analysis and graphical output. The zone boundaries are plotted as black dashed lines, with red text indicating the unstable zone, green text indicating the stable zone, and black text indicating the transition zone. The evaluated soil is plotted as a blue dot which can be compared to the zones to estimate if the soil is potentially susceptible to internal instability.

Step 2: Assess the susceptibility to internal instability

D_{90}	37.500 mm		$30/\log(D_{90}/D_{60})$	101.599
D_{60}	19.000 mm		$15/\log(D_{20}/D_{5})$	19.999
D_{20}	2.561 mm			
D_{5}	0.455 mm			

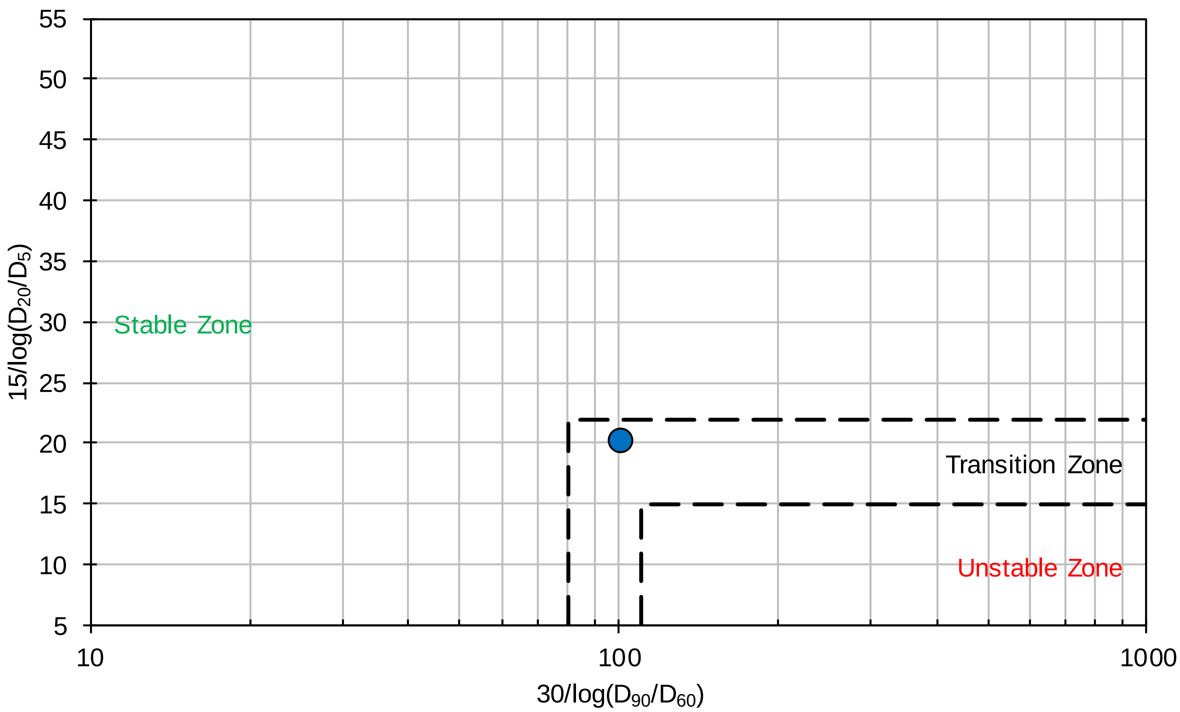


Figure 30. Step 2 of Alternative Method worksheet: Graphical output.

Figure 31 shows the plot options for Figure 30. The minimum and maximum values for the x-axis [$30/\log(D_{90}/D_{60})$] and y-axis [$15/\log(D_{20}/D_{5})$] are user-specified.

Worksheet	Alternative Method		
y-axis bounds			
minimum	5	◄ Enter minimum $15/\log(D_{20}/D_{5})$	Value Primary Min: 5
maximum	55	◄ Enter maximum $15/\log(D_{20}/D_{5})$	Value Primary Max: 55
x-axis bounds			
minimum	10	◄ Enter minimum $30/\log(D_{90}/D_{60})$	Category Primary Min: 10
maximum	1,000	◄ Enter maximum $30/\log(D_{90}/D_{60})$	Category Primary Max: 1000

Figure 31. Step 2 of Alternative Method worksheet: Plot options.

10. Modified Kenney and Lau Method

Kézdi (1979) and Kenney and Lau (1985, 1986) are two of the earliest to assess the susceptibility to internal instability. Li and Fannin (2008) summarized and compared the two methods. The secant slope of the particle-size distribution curve indicates the likelihood of internal instability. Both methods examine the slope of the gradation curve over a discrete interval of its length, but the criterion to establish the size of that interval differs, as illustrated in Figure 32.

Kézdi calculates Terzaghi's D'_{15}/d'_{85} filter ratio over the constant increment of percent finer by mass (*H*) of percent at any point along the gradation curve, where D'_{15} is the particle-size diameter corresponding to 15 percent passing on the cumulative particle-size distribution curve in the coarse fraction and d'_{85} is the particle-size diameter corresponding to 85 percent passing on the cumulative particle-size distribution curve in the finer fraction. In other words, the Kézdi criterion for internal instability is "the slope is flatter than 15% per four times change in particle size." Kenney and Lau calculate the H/F stability index over the increment of *D* to 4*D*. In other words, the Kenney and Lau criterion for internal instability is "the slope is flatter than F% per four times change in particle size."

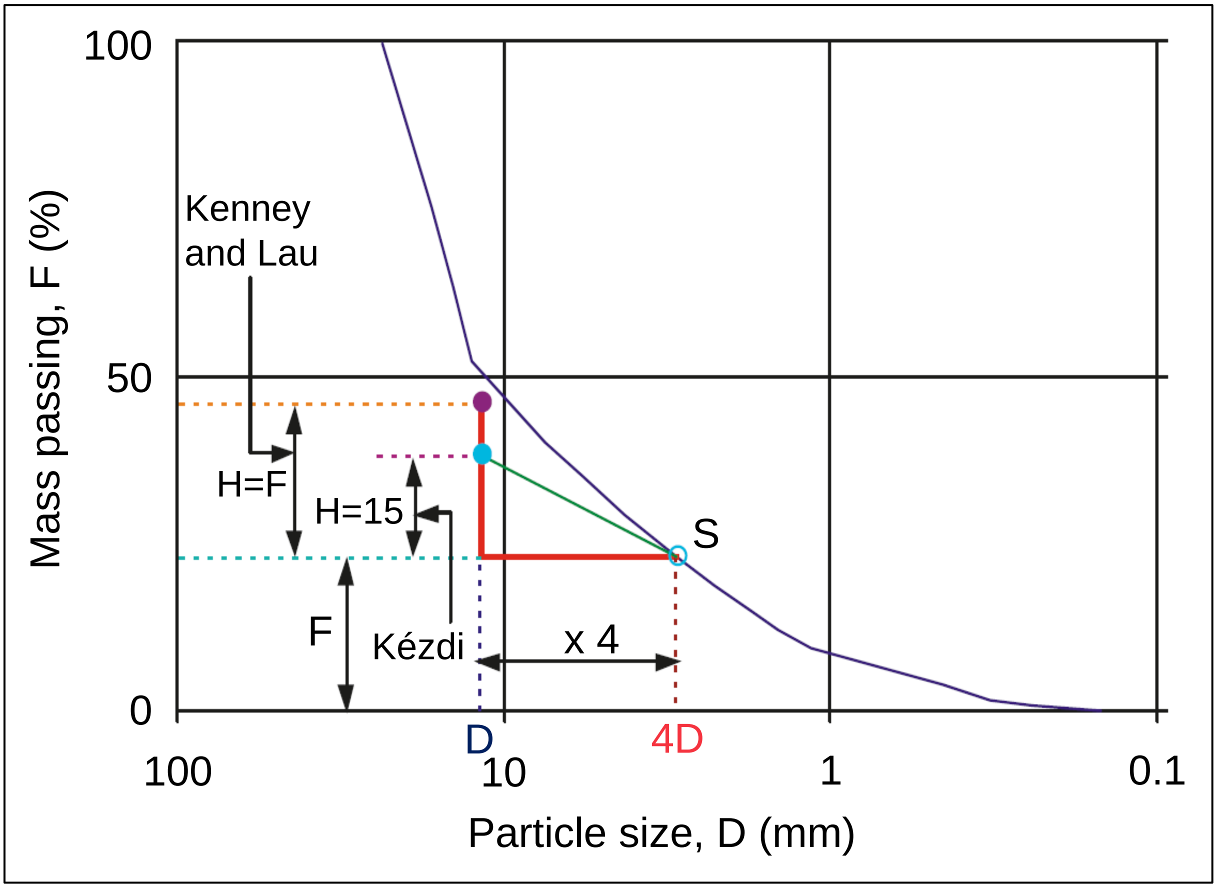


Figure 32. Comparison of Kézdi and Kenney and Lau criteria (adapted from Li and Fannin 2008).

Kenney and Lau (1985, 1986) converted cumulative particle-size distribution curves into shape curves, or *H*-*F* plots, where *F* is the mass fraction smaller than particle diameter *D* (plotted on the x-axis) and *H* is the mass fraction between particle diameter *D* and 4*D* (plotted on the y-axis). An H/F stability index over the increment *D* to 4*D*, which increases in magnitude with progression along the gradation curve, determines if a soil is potentially unstable.

The shape curve is compared to Kenney and Lau's criterion for internal instability. In 1985, they proposed the following criterion for internal instability based on laboratory testing results, as shown in Equation 17.

$$\frac{H}{F} < 1.3 \tag{17}$$

This criterion was subsequently revised in 1986 to Equation 18.

$$\frac{H}{F} < 1 \tag{18}$$

They concluded that the fraction of loose particles within a soil matrix has a maximum value corresponding to whether the gradation is narrowly graded (NG) or widely graded (WG). For NG soils ($C_u \leq 3$), the fraction of loose particles within the soil matrix is less than approximately 30 percent of the total material. For WG soils ($C_u > 3$), the fraction of loose particles is less than approximately 20 percent. Since internal instability depends on the loss of loose particles from within the soil matrix, the fraction of the soil gradation for F>20 percent for WG soils and F>30 percent for NG soils is not considered unstable if it falls below the H/F<1 line. Vertical boundary lines are plotted from H = 0 to $H = F$ to represent these values. The resulting unstable zone is triangular and bounded on the left by the H/F<1 line and on the right by F = 20 percent for WG soils or F = 30 percent for NG soils. If any portion of the shape curve falls within the applicable triangle, that fraction of the soil gradation is considered internally unstable. Figure 33 illustrates the original (1985) and modified (1986) internal instability criteria in (H, F) space.

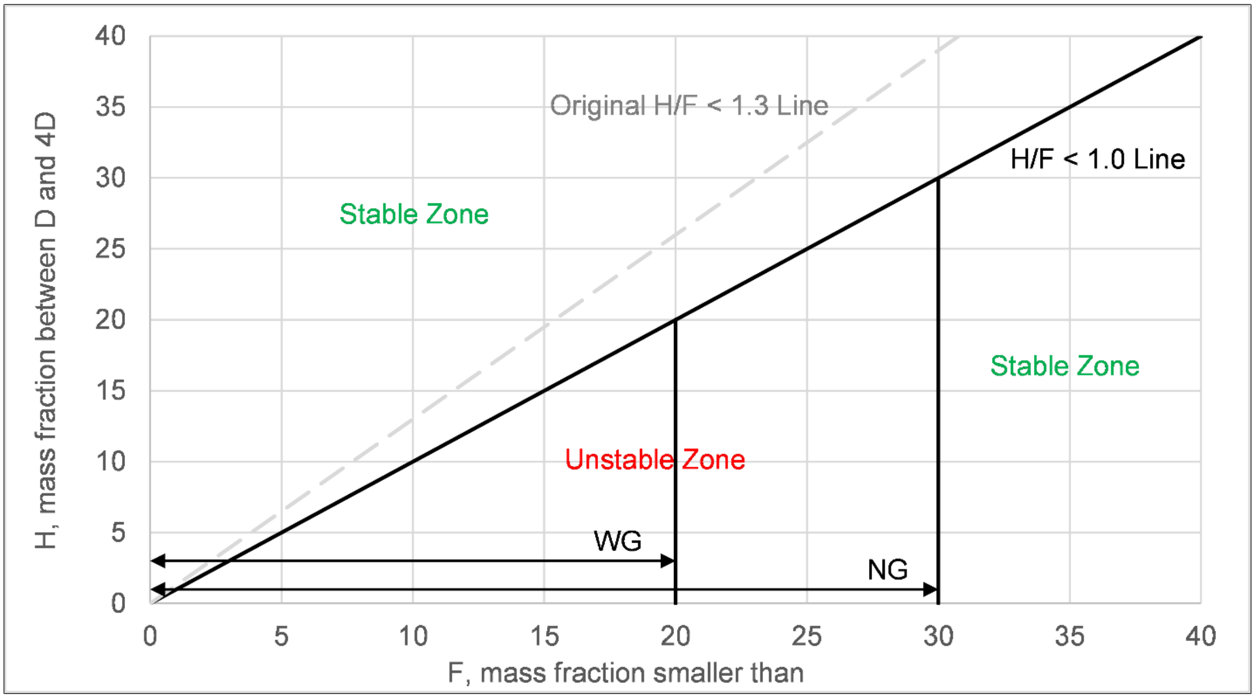


Figure 33. Kenney and Lau (1985, 1986) internal instability criteria in (F, H) space.

Converting the soil gradation into a shape curve can also evaluate the Kézdi method. Whereas the mass increment (H) between particle diameter D and $4D$ for the Kenney and Lau methodology increases along the gradation curve, the mass increment (H) over D'_{15} and d'_{85} for the Kézdi methodology is constant and equal to 15 percent. The resulting unstable zone is rectangular and bounded at the top by H = 15 percent. If any portion of the shape curve falls within the rectangle, that fraction of the soil gradation is considered internally unstable.

Based on a review of laboratory test results in Figure 34, Li and Fannin (2008) concluded that the Kenney and Lau criterion of H/F<1 is a more precise boundary for internal instability for F less than 15 percent, and the Kézdi criterion of H = 15 percent is a more precise boundary for internal instability for F greater than 15 percent.

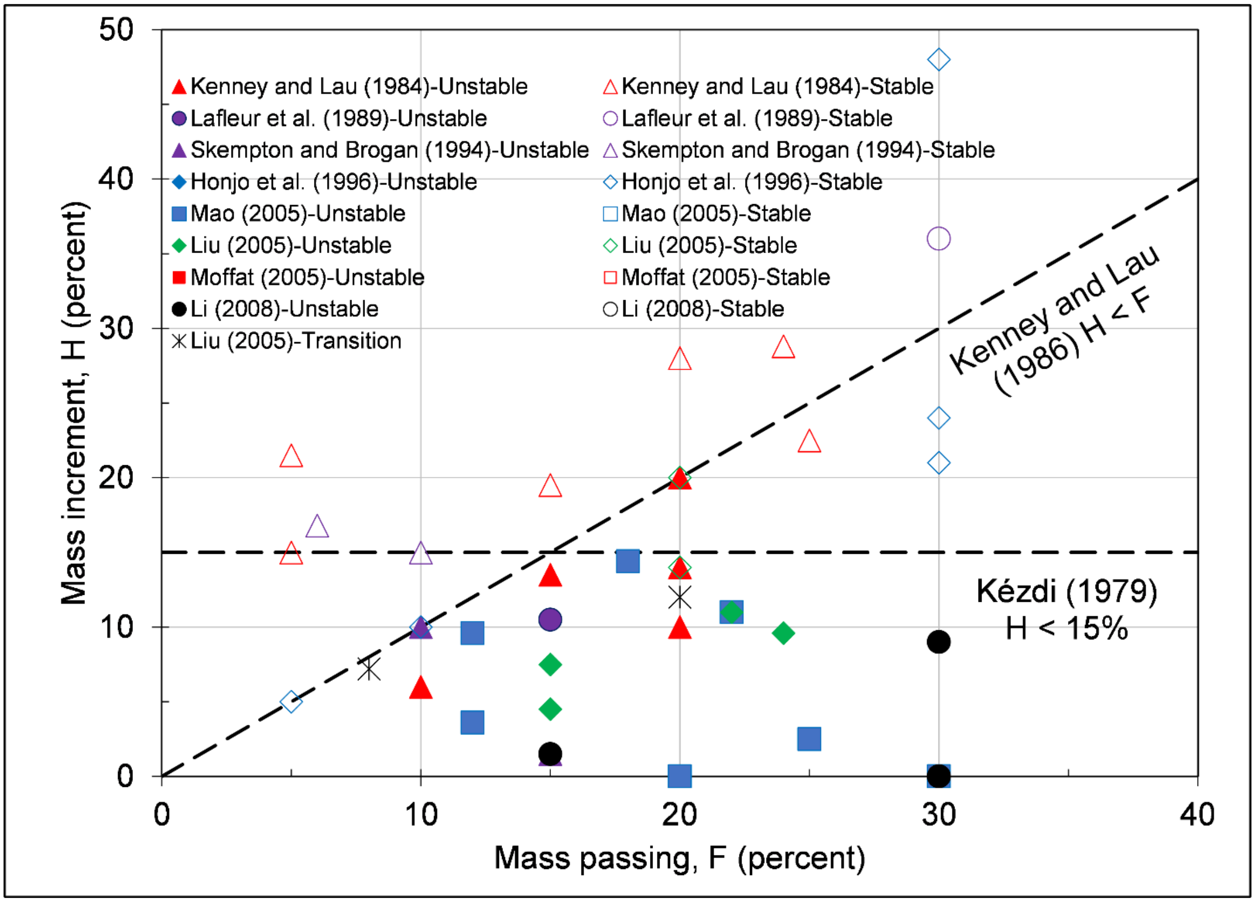


Figure 34. Comparative analysis of the two common criteria to assess internal instability (adapted from Li and Fannin 2008).

As a result, they proposed an approach that combined the two criteria for assessing the susceptibility to internal instability. As Figure 35 illustrates, the resulting unstable zone is trapezoidal, bounded on the left by the Kenney and Lau criterion (H/F<1), on the top by the Kézdi criterion (H<15 percent), and on the right by F<20 percent for WG soils or F<30 percent for NG soils. If any portion of the shape curve falls within the applicable trapezoid, that fraction of the soil gradation is considered internally unstable.

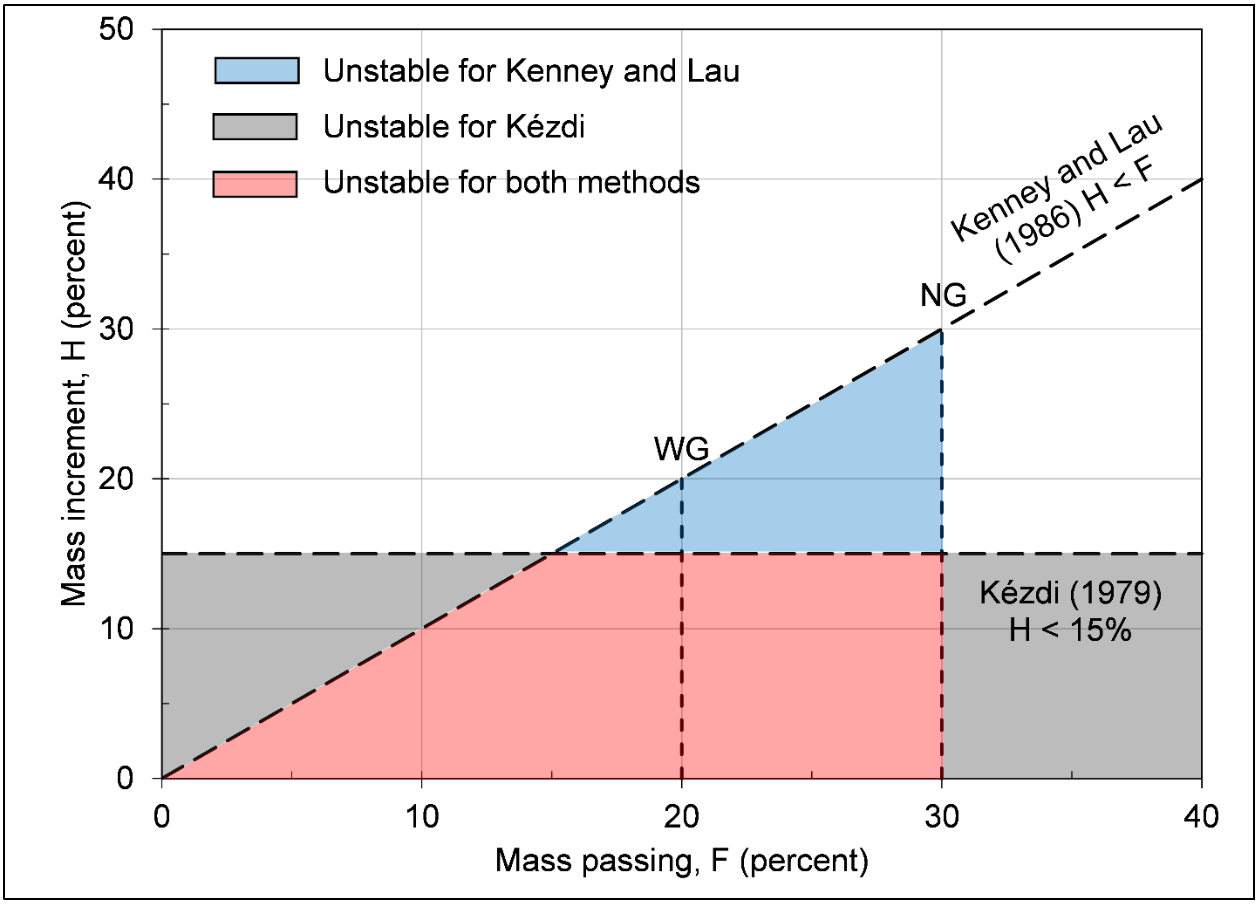


Figure 35. Modified Kenney and Lau method to assess internal instability (adapted from Li and Fannin 2008).

This worksheet assesses the susceptibility of broadly graded and gap-graded soils using the modified Kenney and Lau method of Li and Fannin (2008). As Figure 36 illustrates, the shape curve is obtained based on the particle-size analysis on the Gradation worksheet. These calculations are displayed at the bottom of the worksheet and are not in the print range.

4D = 4 x D

$H = F_{4D} - F$

Gradation Curve

D (mm)	F (%)	4D (mm)	F_{4D} (%)	H (%)	H/F	
45.000	100.0	180.000	100.0	0.0	#N/A	
37.500	90.0	150.000	100.0	10.0	0.111	
25.000	70.0	100.000	100.0	30.0	0.429	
19.000	60.0	76.000	100.0	40.0	0.667	
12.500	48.0	50.000	100.0	52.0	1.083	4(12.5) = 50
9.500	38.0	38.000	90.7	52.7	1.386	
8.000	34.8	32.000	81.2	46.4	1.335	
6.300	30.3	25.200	70.3	40.0	1.321	
4.750	25.0	19.000	60.0	35.0	1.400	
2.000	18.0	8.000	34.8	16.8	0.932	
1.180	14.0	4.720	24.9	10.9	0.780	
0.850	12.0	3.400	21.6	9.6	0.797	
0.600	9.0	2.400	19.0	10.0	1.113	19 - 9 = 10
0.425	4.0	1.700	16.5	12.5	3.134	
0.300	3.0	1.200	14.1	11.1	3.699	
0.250	1.0	1.000	12.9	11.9	11.909	
0.212	0.5	0.848	12.0	11.5	22.952	

Figure 36. Example of obtaining shape curve from cumulative particle-size distribution curve.

Figure 37, Figure 38, and Figure 39 display the calculated shape curve as a blue line along with the individual (*F*, *H*) pairs. The figures display points plotting in the unstable zone as red circles, and points plotting in the stable zone as green circles. Figure 37 illustrates an example for a widely graded soil with a calculated C_u, Figure 38 illustrates an example for a narrowly graded soil with a calculated C_u, and Figure 39 illustrates an example for a widely graded soil without a calculated C_u.

The minimum stability index $(H/F)_{min}$ is determined based on the calculated H/F ratios for the individual (*F*, *H*) pairs, and the mass passing (*F*) where $(H/F)_{min}$ occurs is linearly interpolated from the shape curve. The coefficient of uniformity (C_u) from the Gradation worksheet is also displayed if sufficient particle-size data is available for its calculation.

To define the appropriate boundary for the unstable zone, the primary soil fabric must be characterized as widely graded ($C_u>3$) or narrowly graded ($C_u\leq3$). Use the drop-down list to select the primary soil fabric. When it is calculated, coefficient of uniformity can directly inform the user-specified primary soil fabric; otherwise, use judgment to select the most appropriate primary soil fabric. Based on the user-specified primary soil fabric, the trapezoidal shape of the unstable soil is plotted as a black dashed line, and a description of the three applicable criteria ($H/F<1$, $H<15$ percent, and either widely graded criterion of $F = 20$ percent for widely graded soils or narrowly graded criterion of $F = 30$ percent for narrowly graded soils) is displayed.

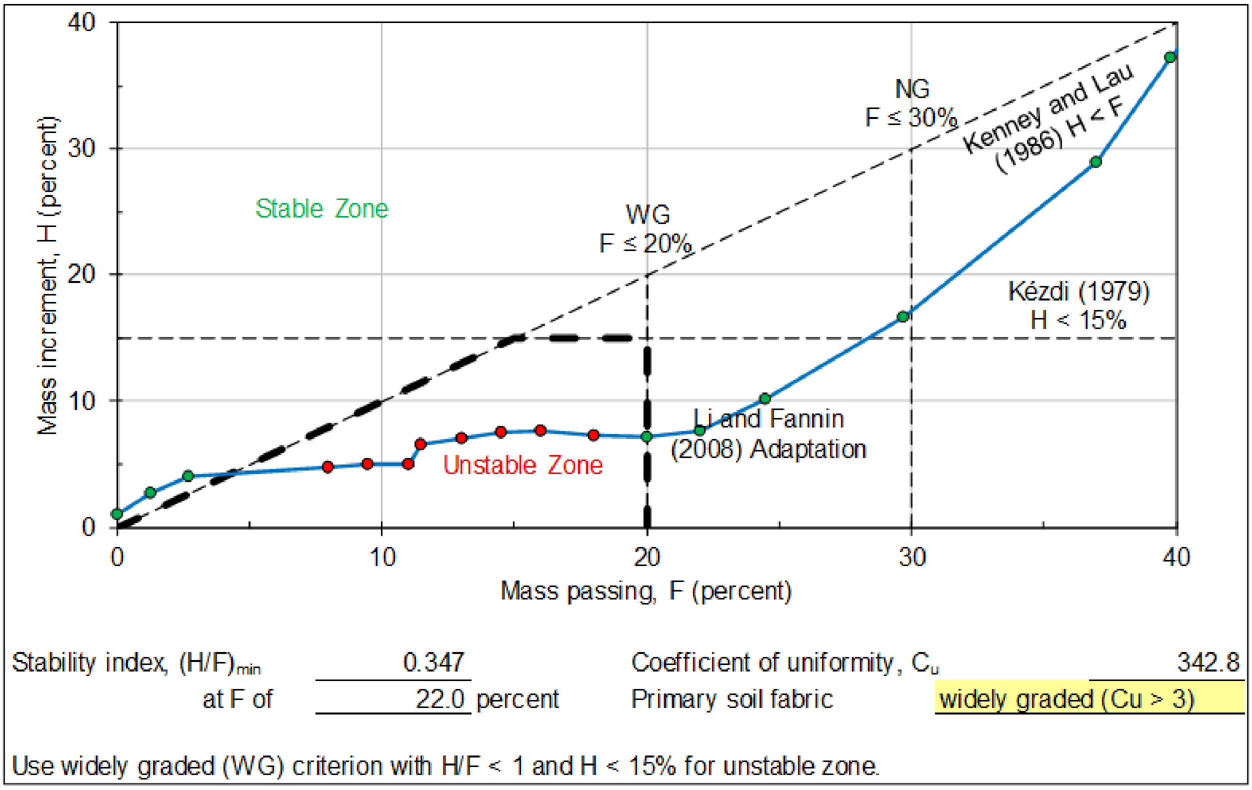


Figure 37. Modified Kenney and Lau Method worksheet:
Shape curve for widely graded soil with coefficient of uniformity.

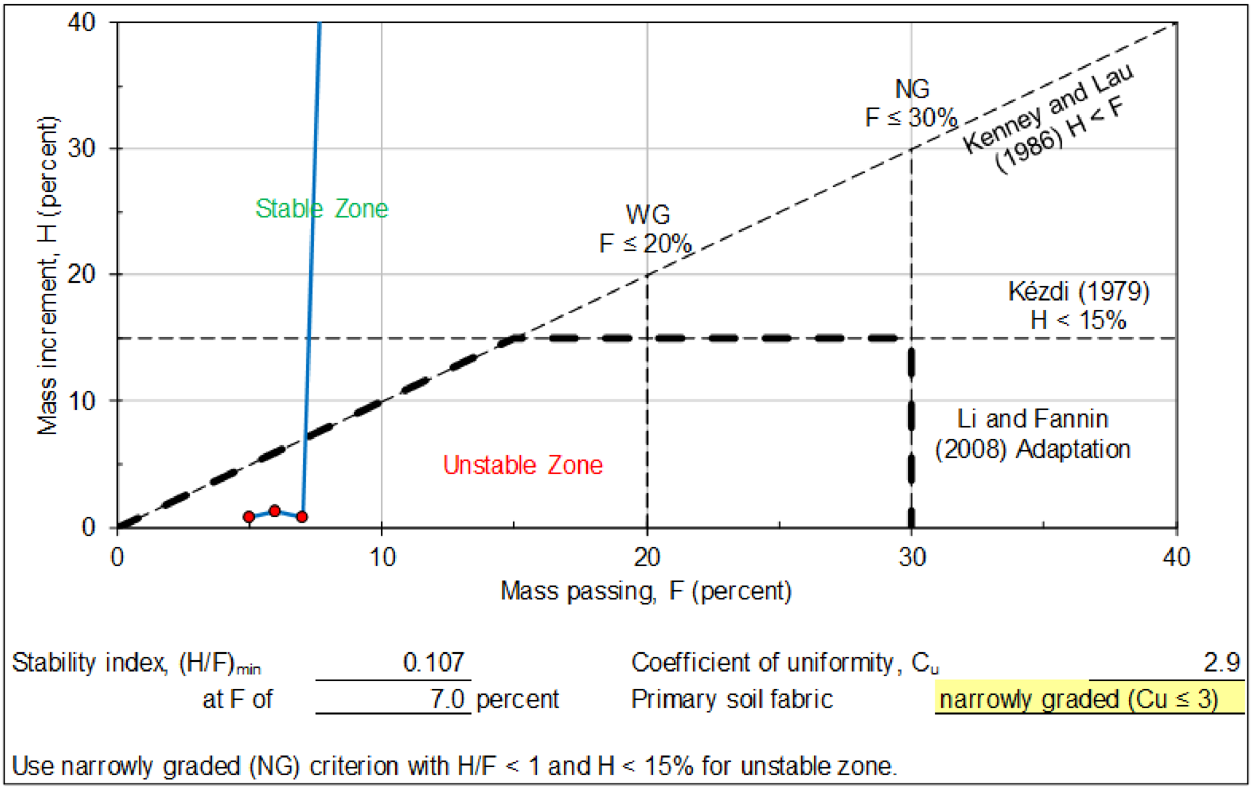


Figure 38. Modified Kenney and Lau Method worksheet:
Shape curve for narrowly graded soil with coefficient of uniformity.

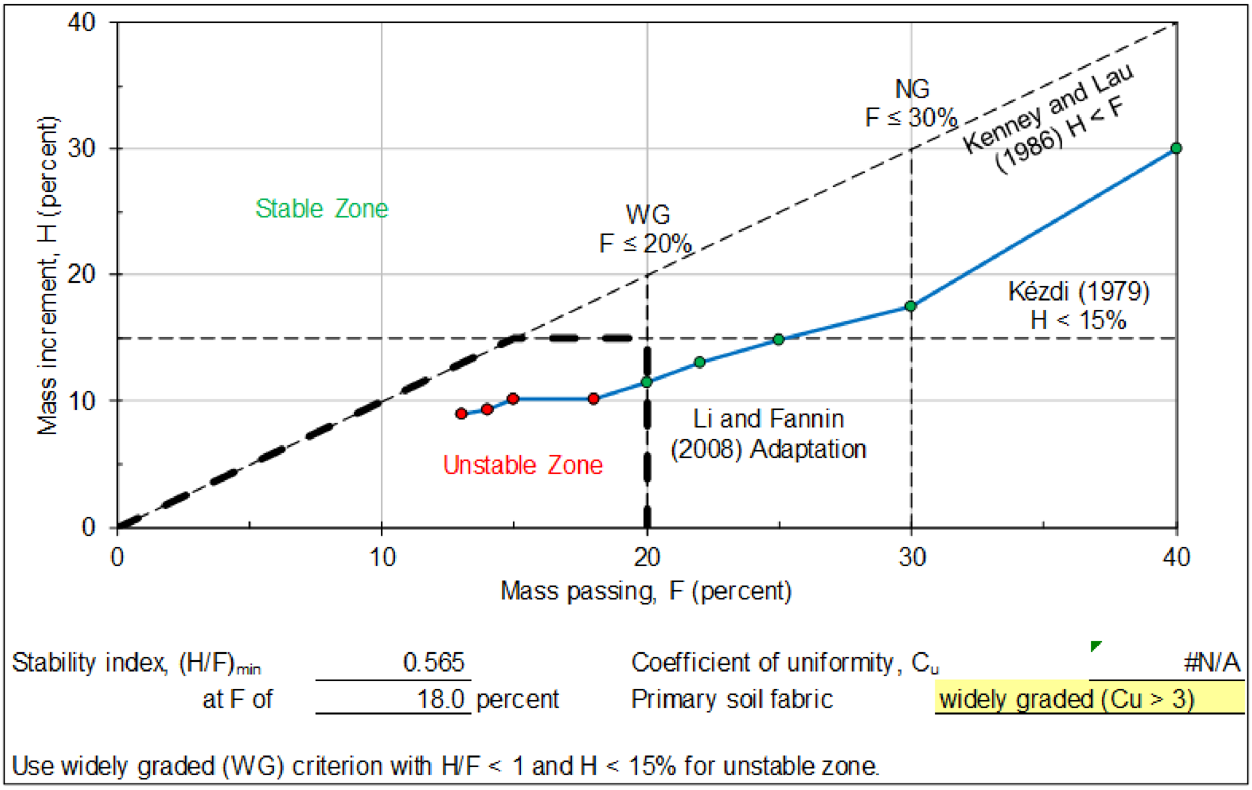


Figure 39. Modified Kenney and Lau Method worksheet:
Shape curve for widely graded soil without coefficient of uniformity.

Figure 40 illustrates an example gradation plot. The cumulative particle-size distribution is plotted as a blue solid line beneath the shape curve. Locations of particle-size deficiency (for gap-graded soils) or self-filtering deficiency (for broadly graded soils) driving the susceptibility to internal instability appear as red circles.

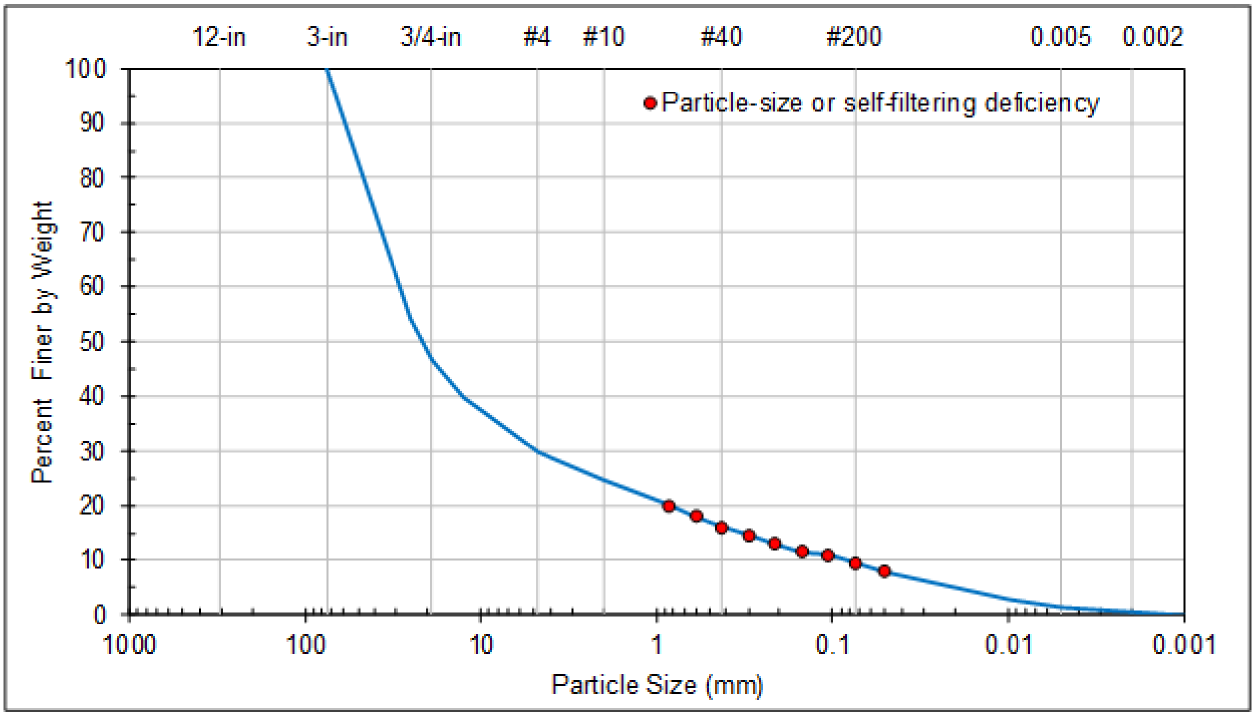


Figure 40. Modified Kenney and Lau Method worksheet: Gradation curve.

11. Mechanism and Amount of Erosion

Douglas et al. (2019) developed a suggested method for the mechanism and amount of internal erosion for non-plastic silt-sand-gravel soils within the envelope of the gradation of the broadly graded soils tested and with similar shaped gradations. Douglas et al. (2019) uses the terminology of International Commission on Large Dams (ICOLD) Bulletin 164 (2017) for suffusion and global backward erosion (GBE).

Suffusion is as defined in chapter 4. GBE is defined as seepage-induced, gravity-assisted particle detachment at unfiltered filtered exits. The voids between the coarser particles are overfilled such that the coarser particles float within the finer particles. The seepage-induced mass loss does not reduce volume or change hydraulic conductivity. Some organizations outside of the U.S. use GBE (United States Society on Dams [USSD 2021]), but USACE considers this internal migration (stoping). Voids develop at the interface with the unfiltered exit that grow (or stope) upward and backward sub-vertically as erosion continues and the temporary roof progressively collapses. Stoping can occur in narrow central core dams constructed with broadly graded cohesionless soils (glacial till) susceptible to internal instability at unfiltered exits. It also occurs at interfaces with open defects in the foundation (e.g., karst bedrock or open-work gravel) or structures embedded in the embankment.

The methodology is based on the ability of the soil to self-filter such that the coarse particles prevent erosion of the medium particles and the medium particles prevent erosion of the fine particles. As shown in Table 1, Douglas et al. (2019) indicated that most of the eroded soil in laboratory tests using a continuing erosion condition was finer than 1.18 millimeter (mm), and the particles between 1.18 and 4.75 mm appeared to self-filter the finer particles. The self-filtering was characterized based on the percentage of the soil between 1.18 and 4.75 mm and the percentage between 0.075 and 1.18 mm. Therefore, the suggested method is based on a gradation split on the No. 16 sieve (1.18 mm).

Table 1
Erosion classes (Douglas et al. 2019).

Erosion Class	**Erosion Amount**
No erosion	No erosion or only a few grams falling from the mesh when first wetted
Very minor erosion	≤0.2% of total sample dry weight
Minor erosion	>0.2% and <1% of total sample dry weight
Medium erosion	1% to 5% of total sample dry weight
Major erosion	>5% of total sample dry weight; or 1% to 5% of total sample dry weight but ≥10% of the dry weight of the finer fraction

Figure 41 shows the test data along with the approximate boundaries separating the data into three categories:

- Internally unstable but self-filtering soils with no erosion or GBE with very minor or minor erosion
- GBE with minor to major erosion
- Suffusion or GBE with major erosion.

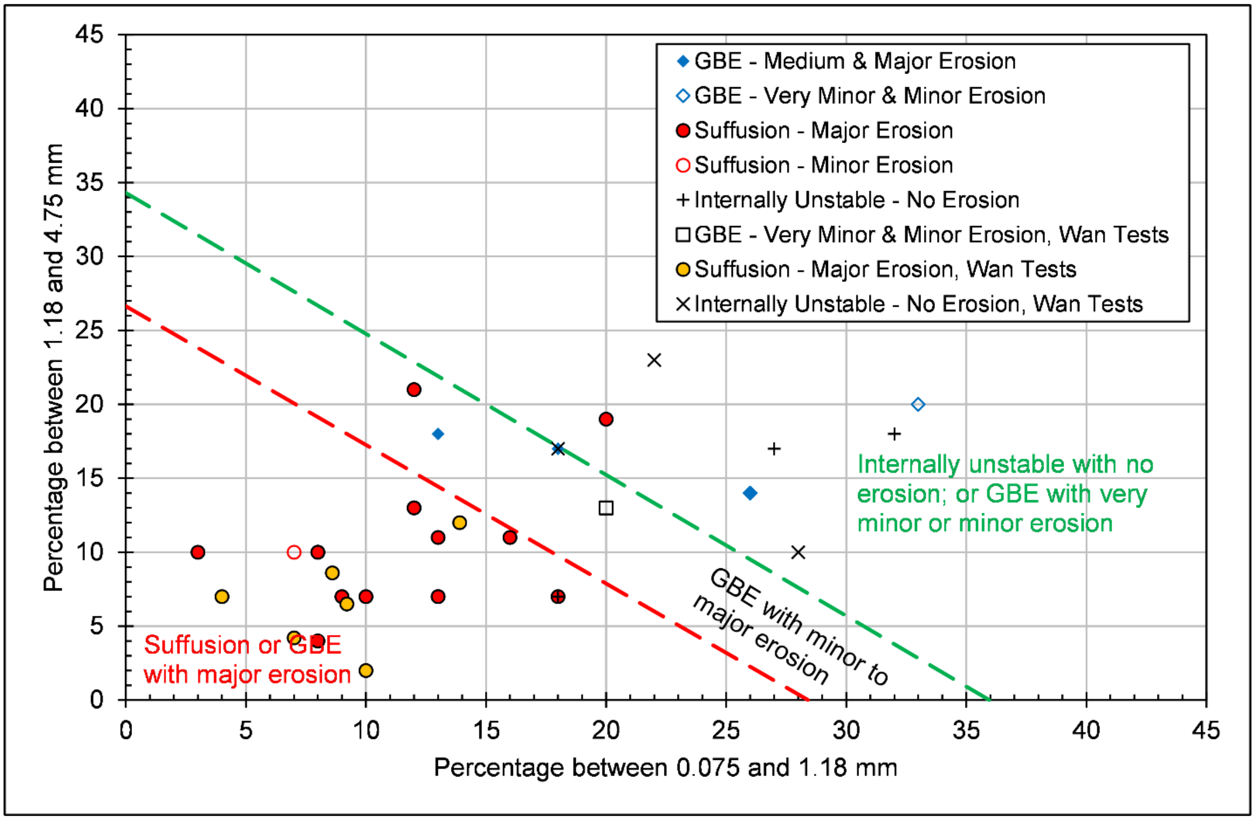


Figure 41. Suggested method for mechanism and amount of internal erosion (Douglas et al. 2019).

11.1. Applicability

This worksheet classifies the mechanism and amount of internal erosion of broadly graded soils using the suggested method of Douglas et al. (2019). The method applies to non-plastic silt-sand-gravel soils within the envelope of the gradation of the broadly graded soils tested and with similar shaped gradations. The method does not apply to gap-graded soils.

In step 1, the user-specified gradation from the Gradation worksheet is plotted as a black line against the gradations of samples exhibiting major and rapid erosion at an average hydraulic gradient of 1 from Douglas et al. (2019) tests (solid red line) and at an average hydraulic gradient of 8 from Wan and Fell (2004) tests (dashed red line), along with the gradations of samples with some or delayed erosion (dashed light blue line) and no or very minor erosion (dashed light green line) from Douglas et al. (2019) tests. This informs whether the user-specified gradation is within the envelope of the gradation of the soils tested and has a similar gradation shape.

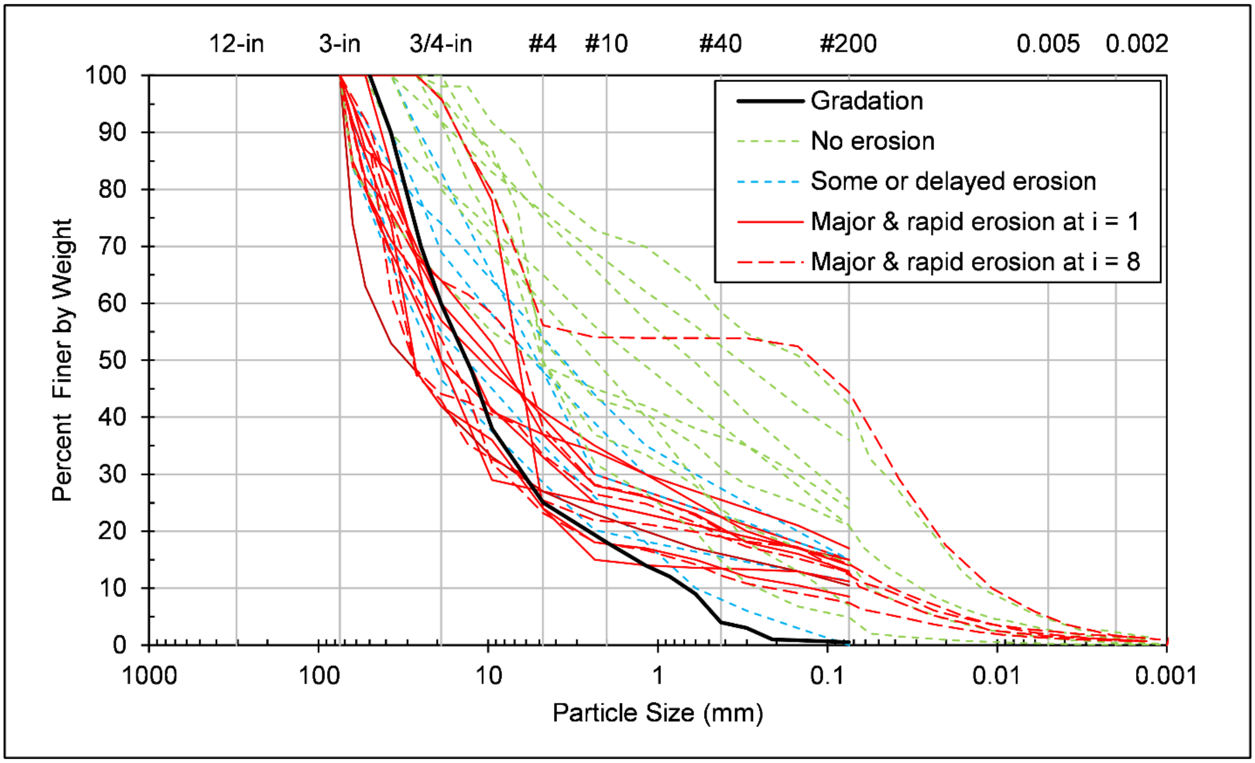


Figure 42. Step 1 of Mechanism and Amount of Erosion Worksheet: Gradation comparison.

11.2. Methodology

In step 2, based on the particle-size analysis on the Gradation worksheet, the percentage of the soil between 1.18 and 4.75 mm (passing the No. 4 sieve and retained on the No. 16 sieve) and the percentage between 0.075 and 1.18 mm (passing the No. 16 sieve and retained on the No. 200 sieve) are calculated. If these particle sizes are not available for the specified gradation, these calculations cannot be performed.

The approximate boundary for no erosion of internally unstable but self-filtering soils with no erosion, or GBE with very minor or minor erosion, is plotted as a green dashed line, and the approximate boundary for suffusion or GBE with major erosion is plotted as a red dashed line, as illustrated in Figure 43. Between these two boundaries is a zone where GBE with minor to major erosion occurs. The mechanisms of internal erosion and erosion class (amount of internal erosion) are provided below the plot.

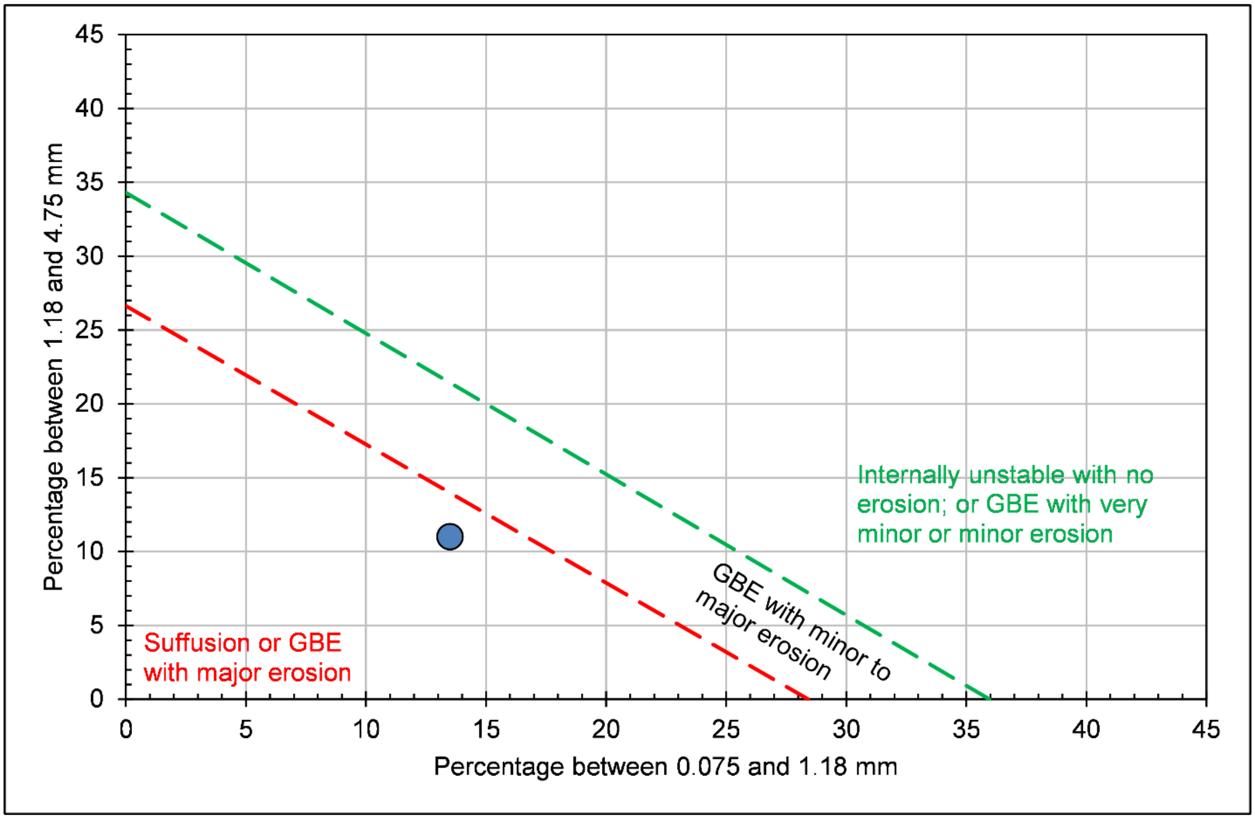


Figure 43. Step 2 of Mechanism and Amount of Erosion worksheet: Graphical output.

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Appendix A. Acronym List

ASTM	American Society for Testing and Materials
CF	Clay-Size Fraction
CPD	Computer Program Document
FC	Fines Content
GBE	Global Backward Erosion
HEC	Hydrologic Engineering Center
ICOLD	International Commission on Large Dams
IUS	Internally Unstable Soil
IWR	Institute for Water Resources
LL	Liquid Limit
NG	Narrowly Graded
NP	Non-Plastic
PI	Plasticity Index
PL	Plastic Limit
QC	Quality Control
RMC	Risk Management Center
UDF	User-Defined Function
U.S.	United States
USACE	U.S. Army Corps of Engineers
USCS	Unified Soil Classification System
USSD	United States Society on Dams
WG	Widely Graded