RMC Pipe Service Life Toolbox

RMC Internal Erosion Suite

RMC-CPD-2023-11

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 remaining service life of steel, aluminum, concrete, iron, plastic, and clay pipe materials, especially for the invert, when the existing condition is unknown due to lack of recent detailed inspection. This assessment supports the evaluation of the likelihood of a flaw or open defect existing which can lead to internal migration of the adjacent soil into the open defect or concentrated leak erosion adjacent to the pipe due to flow out of the open defect.

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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.

David Schaaf, 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 Pipe Service Life 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.
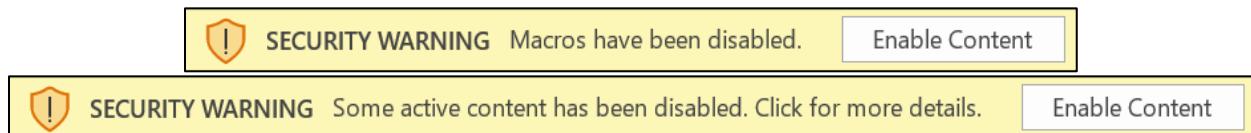
Figure 1. Security warning message bars with the "Enable Content" option to enable macros.

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, 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 migration is the erosion of soil particles into open defects that initiates voids at the interface with the soil that expand (or stope) upward as temporary roofs collapse. Soil particles migrate downward primarily due to gravity and are aggravated by seepage or precipitation. For foundation defects, soil particles that drop to the bottom of the void are carried away by seepage through an unfiltered exit. For conduits, pipes, and culverts, the soil particles are carried by flow through the pipe. This usually results in sinkhole formation. This toolbox helps assess the likelihood of an open defect (flaw) in conduits, pipes, and culverts of unknown condition. The RMC Concentrated Leak Erosion (Initiation) and RMC Backward Erosion Piping (Progression) Toolboxes help assess the likelihood of internal erosion along conduits, pipes, and culverts.

Using this toolbox is not necessary if the condition of the pipe and presence of open defects are known to exist, as shown in Figure 8, or from a video inspection, as shown in Figure 9. Even if a video inspection reveals no defects, that does not necessarily mean none exist. The invert of the pipe must be clear of debris, bedload, and water/effluent to determine the actual condition. This is extremely important because the invert of the pipe is the area most susceptible to damage due to its routine exposure to flow and bedload. If these conditions are met (full interior of pipe clearly visible for walkthrough or video inspection within 5 years of the evaluation) and no defects are found, using this toolbox is not necessary, because the presence of an open defect is considered remote.

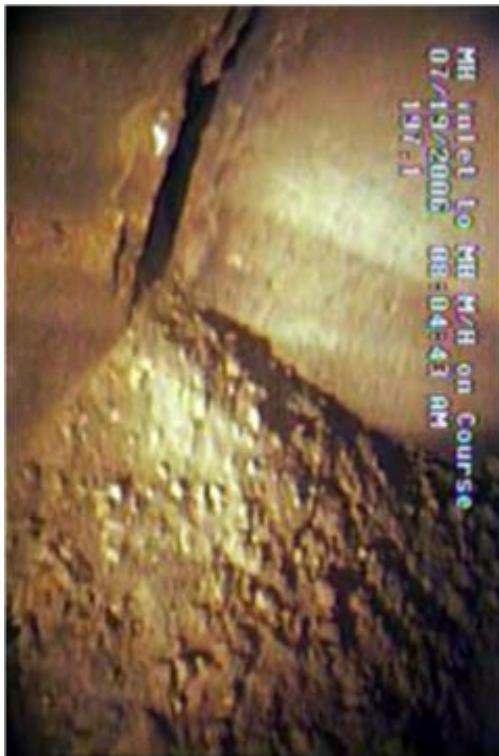**Figure 8. Deterioration (flaw) of galvanized corrugated steel pipe.**

Figure 9. Separated joint (flaw) of reinforced concrete pipe.

In addition to embedded pipes whose condition is known, those that have been constructed "up and over" embankments or floodwalls (or in the overbuild section of an embankment) typically do not require analysis with the toolbox because they usually are not critical from an internal erosion standpoint. Pipes located up and over can have defects, but the embankment or supporting material around a floodwall usually cannot be transported through the defect. Pipes located in the extreme upper reaches of the embankment (in the overbuild or freeboard section) generally do not have enough hydraulic gradient to transport surrounding material through an open defect. Even if embankment material is lost through the open defect of a pipe in the overbuild or freeboard section, only a small portion of the embankment is affected due to the location of the pipe.

This toolbox estimates the remaining service life for steel, aluminum, concrete, ductile iron, cast iron, plastic, and clay pipes. The assessment of steel, aluminum, and concrete pipes is associated with degradation along the invert of the gravity flow pipes based on numerous historic testing experiments, field studies, and the actual service life of pipes from numerous individual state Department of Transportation studies. Iron (ductile and cast) pipes are typically used for utility distribution lines where bedload along the invert does not exist. Therefore, iron pipes are evaluated for external corrosion effects. Plastic pipes are being used much more frequently. They offer potential advantages when it comes to corrosion resistance, ease of installation, invert wear, etc. However, much less is known about the long-term performance of plastic pipes embedded within embankments. The toolbox uses a default service life for plastic pipes until better historic performance information becomes available. Lastly, various types of clay pipes have been used for centuries to convey water and other effluent. The performance of clay pipes is typically driven by joint separation caused by external protrusions (such as tree roots) or differential settlement. The toolbox uses a default service life for clay pipes when their condition is unknown.

Other types of pipe materials could potentially be embedded within or under an embankment or floodwall. This toolbox can provide a rough estimate of remaining service life by considering both the pipe's purpose/use and base material. Use this information to select the most appropriate corresponding pipe material from the toolbox for evaluation. Table 1 provides several examples for reference.

Table 1
Alternative pipe materials.

Pipe Material	Pipe Use/Purpose	Suggested Worksheet
Structural steel	Gravity drainage flow	Steel and Aluminum
Structural steel	Other uses	Iron (modified pipe thickness)
Fiberglass	Any use	Plastic
Brick or masonry	Any use	None recommended
Ceramic	Any use	Clay
Lead	Gravity drainage flow	Steel and Aluminum
Lead	Other uses	Iron
Coal tar wood fiber	Any use	None recommended
Asbestos cement	Any use	Concrete

Engineer Manual (EM) 1110-2-2902 (USACE 2020) provides risk-informed guidance for the life cycle of conduits, pipes, and culverts. There are important differences between this manual and EM 1110-2-2902 with respect to a pipe's operating environment. The toolbox was developed to estimate the service life of an existing pipe to inform evaluation of an internal migration potential failure mode during a risk assessment. The process focuses on wear along the invert of the pipe and/or external corrosion. A simplified process was developed using a myriad of operating environments to make it general enough for widespread use but simple enough to use with basic, readily available data.

EM 1110-2-2902 is geared toward design of new pipes with respect to their anticipated operating environment. This includes the ability to safely carry all structural loads, deflection criteria, and handling/transport considerations. EM 1110-2-2902 references existing design procedures as much as possible, and includes information from other agencies, organizations, and groups. The procedures incorporate inherent safety factors, operating restrictions, and other performance issues to account for uncertainty as part of the design process.

5.   Steel and Aluminum Pipes

Galvanized (zinc-coated), corrugated steel pipes (CSPs) are commonly used for gravity drainage structures in many levee embankments and floodwalls in the USACE portfolio. They are much less common in USACE dams because of significant structural loads acting on the pipe and high-flow velocities. They may be present in low-head dams. Corrugated aluminum pipes (CAPs) are also widely used, typically when potential corrosion causes concern from the soil surrounding the pipe or the effluent flowing through the pipe. Non-corrugated steel and aluminum pipes are used but much less frequently than corrugated pipes. This worksheet can assess both corrugated and non-corrugated steel and aluminum pipes.

5.1.   Pipe Material and Shape Characterization

Step 1 characterizes the pipe material and shape. Select the pipe material using the drop-down list as shown in Figure 10. CSP galvanized with a protective zinc coating, aluminum-coated Type 2 CSP (ALCLAD® or equivalent), and aluminum-zinc alloy-coated CSP (Galvalume® or equivalent) can be evaluated.

Step 1: Characterize the pipe material and shape	
Pipe material	Aluminum-coated Type 2 CSP (ALCLAD® or equivalent)

Figure 10. Step 1 of Steel and Aluminum Pipe worksheet: Pipe material characterization.

Select the pipe shape using the drop-down list as shown in Figure 11. Circular, box, and arch pipe can be evaluated. For Circular, specify the interior diameter as illustrated in Figure 11. For Box, specify the interior depth (height) and interior width as illustrated in Figure 12. For Arch, choose the pipe arch size based on American Society for Testing and Materials (ASTM) A760 from the drop-down list, and the equivalent diameter displays as illustrated in Figure 13. For Other for pipe arch size, specify the pipe arch size and equivalent diameter as illustrated in Figure 14. Cells that do not apply have a gray background.
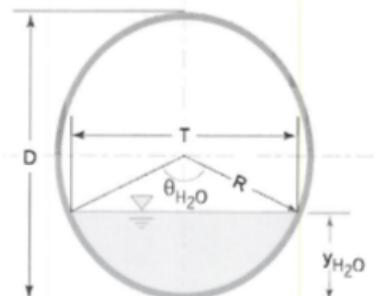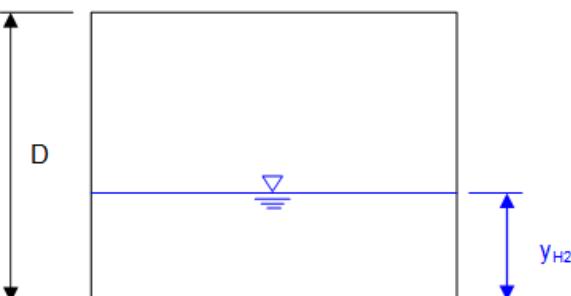
Figure 11. Step 1 of Steel and Aluminum Pipe worksheet: Circular pipe dimensions.
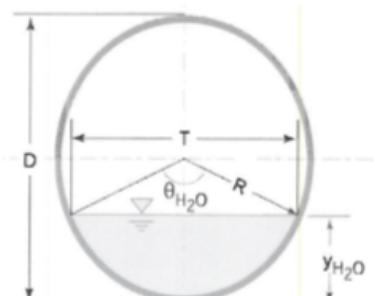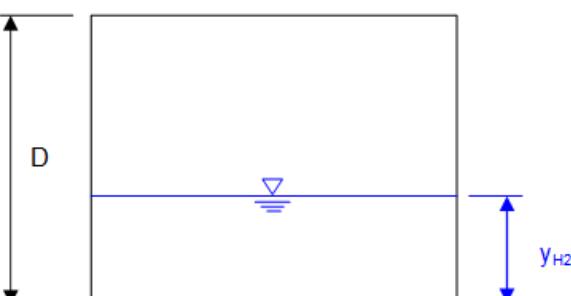
Figure 12. Step 1 of Steel and Aluminum Pipe worksheet: Box pipe dimensions.
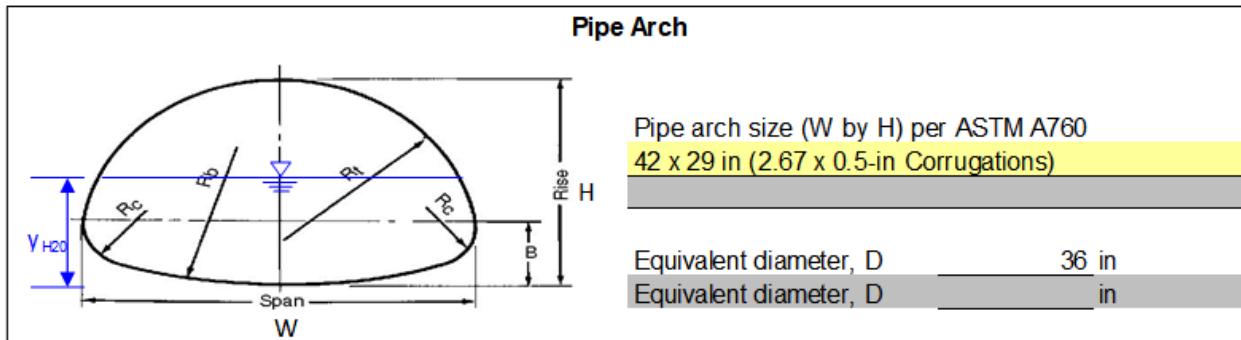
Figure 13. Step 1 of Steel and Aluminum Pipe worksheet: ASTM A760 arch pipe dimensions.
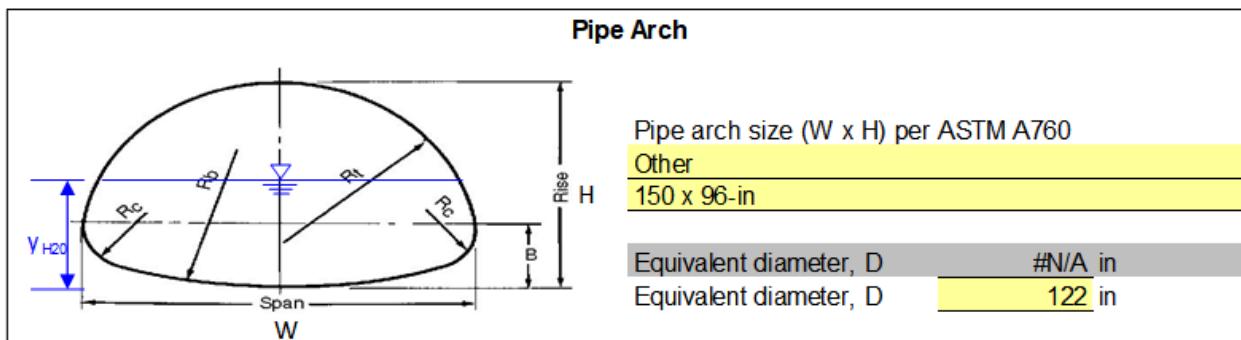
Figure 14. Step 1 of Steel and Aluminum Pipe worksheet: User-specified arch pipe dimensions.

5.2. Flow Velocity Characterization

Step 2 uses Manning's equation (Equation 1) to calculate the velocity (ft/sec) of flow through the pipe for significant (but not extreme) rainfall events.

$$V = \left(\frac{1.486}{n}\right) R^{2/3} S^{1/2} \tag{1}$$

where:

n = Manning's roughness coefficient for the pipe material
R = hydraulic radius of the pipe (ft)
S = steepest pipe invert slope (ft/ft)

Specify the Manning's roughness coefficient (n). Various sources are available for n values, but in most cases, the pipe has either a corrugated or smooth interior flow surface. For pipes with an interior corrugated flow surface, the suggested value is 0.024. If the interior flow surface is smooth, the suggested value is 0.012 (USACE 2020).

The hydraulic radius (R) is a function of the pipe shape and depth of flow, as calculated in Equation 2.

$$R = \frac{A}{P_w} \tag{2}$$

where:

A = cross-sectional area of the flow in the pipe (ft²)
P_w = wetted perimeter of the flow in the pipe (ft)

To obtain A and P_w, the depth of flow in the pipe during a significant (but not extreme) rainfall event (y_{H2O}) for each pipe shape is required. Instead of a selecting a flow depth, the flow depth is normalized with the interior pipe depth (height) from step 1. Select the normalized flow depth (y_{H2O}/D) using the drop-down list. Normalized flow depths of 100, 87.5, 75, 50, 25, 10, and 5 percent can be evaluated. If a pipe was in service for several years, it may have a rust line that can inform the depth of flow. If the flow depth is unknown, the suggested normalized flow depth is 25 percent. The flow depth (d) is calculated by multiplying the normalized flow depth (y_{H20}/D) by the interior pipe depth (D), as illustrated in Figure 15.

Step 2: Characterize the flow velocity through the pipe

Flow Depth
Normalized depth of flow during a significant (but not extreme) event, y_{H20}/D 25 percent
  Note: Select a value of 25% unless there is solid evidence to suggest
  that typical depth of flow within the pipe should be a different value.
Flow depth, $d = y_{H20} = (y_{H20}/D) D$ 0.75 ft

Figure 15. Step 2 of Steel and Aluminum Pipe worksheet: Flow depth.

The pipe shape selected in step 1 affects the calculations of A and P_w in step 2. For a circular pipe, the interior diameter from step 1 is used to calculate A and P_w as illustrated in Figure 16. For a pipe arch, the calculations are the same as for circular pipe but use the equivalent interior diameter. For a box pipe, the interior depth (height) and interior width are used to calculate A and P_w as illustrated in Figure 17. Cells that do not apply have a gray background.

Circular Pipe or Pipe Arch
Circular segment height, $h = d$ (for $d < r$) and $h = 2r - d$ (for $d \geq r$)   0.75 ft
Central angle, $\theta = 2a\cos[(r - h) / r]$ 2.09 rad
Circular segment area, $K = r^2[\theta - \sin(\theta)] / 2$ 1.38 ft²
Arc length, $s = r\theta$ 3.14 ft
Flow area, $A = K$ (for $d < r$) and $A = \pi r^2 - K$ (for $d \geq r$)   1.38 ft²
Wetted perimeter, $P_w = s$ (for $d < r$) and $P_w = 2\pi r - s$ (for $d \geq r$)   3.14 ft

Figure 16. Step 2 of Steel and Aluminum Pipe worksheet: Circular pipe or pipe arch geometric parameters.

Box Pipe
Flow area, $A = Wd$ 3.00 ft²
Wetted perimeter, $P_w = W + 2d$ 5.50 ft

Figure 17. Step 2 of Steel and Aluminum Pipe worksheet: Box pipe geometric parameters.

Specify the steepest slope of the pipe invert (S). Most pipes have a consistent slope along their invert length, but it is possible to have multiple slopes if gate wells or manholes are along the length of the pipe.

If the pipe has more than one invert slope, enter the steepest slope. The units are dimensionless (feet of vertical change divided by feet of horizontal length).

Characterize the flow velocity through the pipe using the following mapping scheme:

- Low velocity flow ($V \leq 5$ ft/sec)

- Moderate velocity flow (5 ft/sec $< V \leq 10$ ft/sec)

- High velocity flow (10 ft/sec $< V \leq 15$ ft/sec)

- Very high velocity flow ($V > 15$ ft/sec)

The calculated flow velocity is compared against this mapping scheme as illustrated in Figure 18.

Flow Velocity	
Manning's roughness coefficient for pipe material, n	0.012
(Use 0.024 for corrugated pipes and 0.012 for smooth pipes)	
Hydraulic radius, R = A / P_w	0.55 ft
Steepest slope of pipe invert, S	0.0100 ft/ft
(e.g., use 0.01 for 1 percent; use 0.00001 for a flat slope instead of zero.)	
Flow velocity, $V = (1.486/n)R^{2/3}S^{0.5}$	8.27 ft/sec
Flow velocity characterization	Moderate

Figure 18. Step 2 of Steel and Aluminum Pipe worksheet: Flow velocity characterization.

5.3. Flow Frequency Characterization

Step 3 characterizes the frequency of significant flow through the pipe. Significant flow is defined as a high enough velocity to move a slight to moderate abrasive bedload (for example, sand or a sand-type mixture) along the invert of the pipe (Potter 1988). For this toolbox, slight to moderate abrasive bedload is relative to other bedload types such as silts/clays (non- or low abrasive) or gravels/cobbles (extremely abrasive). Select the frequency of significant flow through the pipe using the drop-down list. The following generalized flow frequencies can be evaluated:

- Pipe is subjected to constant or nearly constant significant flow. The flow velocity varies through time and over the course of events, but there is generally always movement of water through the pipe throughout its service life. This is usually not the case for surface drainage pipes, but there are exceptions.

- Pipe flows many times during a typical year due to precipitation, groundwater, snowmelt, or other causes. This classification is likely associated with a region that receives more than 20 inches of precipitation in most years. Although the pipe is in a high-precipitation region, it may not be exposed to frequent flows, depending on how the inlet is configured.

- Pipe is in a region that receives less than 20 inches of precipitation annually or is not situated to carry flow very often.

- Pipe is rarely, if ever, subjected to flow, either because it is in an arid region (less than 10 inches of precipitation annually), or because it is configured to collect very little runoff or flow.

U.S. Climate Normals (https://www.ncei.noaa.gov/products/land-based-station/us-climate-normals) from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) can help assess typical climate conditions, including average annual precipitation for a given location. Official normals are updated every 10 years and calculated for a uniform 30-year period.

For a specified significant flow frequency of Continuous or Frequent, the flow likelihood is Likely. For a specified significant flow frequency of Infrequent or Rare, the flow likelihood is Unlikely.

5.4. Bedload Characterization

Step 4 characterizes the bedload that is moved along the invert of the pipe during significant flow events. Select the bedload using the drop-down list. The following bedload material categories can be evaluated:

- Sand: Sands or sandy soil mixtures without gravels or cobbles

- Silt: Silts, loess, or silty soil mixtures without gravels or cobbles

- Clay: Clays or clayey soil mixtures without gravels or cobbles

- Loam: Soils with roughly equal proportions of sand, silt, and clay without gravels or cobbles

- Gravel-Minor: Soil mixtures with relatively minor amounts of gravels or cobbles

- Gravel-Major: Soil mixtures with a significant amount of gravels or cobbles

- Rock: Primarily gravels or cobbles

- None: No bedload present during flow events

- Other: Bedload not adequately characterized by existing categories

5.5. Flow Abrasiveness Characterization

Step 5 characterizes the flow abrasiveness based on the flow velocity through the pipe, frequency of significant flow, and bedload material using Table 2 through

Table 5. This step has no user-specified input unless the bedload is Other. In this case, select the relative flow abrasiveness using the drop-down lists for each flow velocity category. The relative flow abrasiveness must be consistent with the flow velocity (as the flow velocity increases, the relative flow abrasiveness must increase or stay the same, depending on the bedload).

A relative flow abrasiveness of N/A in Table 2 through

Table 5 represents scenarios that are not possible because lower velocities cannot move heavier bedloads through the pipe (Potter 1988). For a relative flow abrasiveness of N/A, a warning message displays, the analysis is stopped, and the remaining steps have a gray background.

Table 2
Relative flow abrasiveness for continuous flow.

Flow Velocity	Relative Flow Abrasiveness				
	Sand or Loam	Silt or Clay	Gravel-Minor	Gravel-Major or Rock	None
Low	Abrasive	Abrasive	N/A	N/A	Non-Abrasive
Moderate	Abrasive	Abrasive	Extremely Abrasive	N/A	Abrasive
High	Extremely Abrasive	Abrasive	Extremely Abrasive	Extremely Abrasive	Abrasive
Very High	Extremely Abrasive	Extremely Abrasive	Extremely Abrasive	Extremely Abrasive	Extremely Abrasive

Table 3
Relative flow abrasiveness for frequent flow.

Flow Velocity	Relative Flow Abrasiveness					
	Sand	Silt or Clay	Loam	Gravel-Minor	Gravel-Major or Rock	None
Low	Non-Abrasive	Non-Abrasive	Non-Abrasive	N/A	N/A	Non-Abrasive
Moderate	Abrasive	Non-Abrasive	Abrasive	Abrasive	N/A	Non-Abrasive
High	Abrasive	Abrasive	Abrasive	Extremely Abrasive	Extremely Abrasive	Abrasive
Very High	Extremely Abrasive	Abrasive	Extremely Abrasive	Extremely Abrasive	Extremely Abrasive	Abrasive

Table 4
Relative flow abrasiveness for infrequent flow.

Flow Velocity	Relative Flow Abrasiveness			
	Sand, Silt, Clay, or Loam	Gravel-Minor	Gravel-Major or Rock	None
Low	Non-Abrasive	N/A	N/A	Non-Abrasive
Moderate	Non-Abrasive	Abrasive	N/A	Non-Abrasive
High	Abrasive	Extremely Abrasive	Extremely Abrasive	Non-Abrasive
Very High	Abrasive	Extremely Abrasive	Extremely Abrasive	Abrasive

Table 5
Relative flow abrasiveness for rare flow.

Flow Velocity	Relative Flow Abrasiveness				
	Sand or Silt	Clay or Loam	Gravel-Minor	Gravel-Major or Rock	None
Low	Non-Abrasive	Non-Abrasive	N/A	N/A	Non-Abrasive
Moderate	Non-Abrasive	Non-Abrasive	Abrasive	N/A	Non-Abrasive
High	Abrasive	Non-Abrasive	Extremely Abrasive	Extremely Abrasive	Non-Abrasive
Very High	Abrasive	Abrasive	Extremely Abrasive	Extremely Abrasive	Non-Abrasive

5.6. Aggressive Deterioration Environment Characterization

Step 6 characterizes the aggressive deterioration environment. The factors depend on the pipe material. The service life of traditional galvanized CSP and aluminum-zinc coated CSP (Galvalume® or equivalent) is very similar in wear along the invert of the pipe (Potter et al. 1991). Cells that do not apply have a gray background. The aggressive deterioration environments for these pipe materials include:

- Soft water: Water with calcium carbonate concentration less than 60 parts per million (ppm) flowing through the pipe is more detrimental to pipe corrosion. Water with this characteristic lacks the ability to provide partially protective scales or films on the inside of the pipe that hinder corrosion (Bednar 1989). If the flow through the pipe is only from surface water runoff, consider it soft unless supporting data proves otherwise. The map of water hardness (https://www.usgs.gov/media/images/map-water-hardness-united-states) published by the U.S. Geological Survey (USGS) can help assess the potential for soft water when site-specific groundwater hardness data is unavailable.

- Stray electrical current: Excessive corrosion damage is sometimes caused by stray electrical current (interference) from other direct current (DC) sources. Examples of these sources include impressed cathodic protection systems on other utilities/pipes, DC-powered transit systems in the immediate vicinity, and electrical installations (Bonds 2017).

- Highly acidic conditions: The environment is highly acidic if the soil surrounding the pipe or the effluent flowing through the pipe has a pH less than 5. Known acidic environments include highly urbanized areas as well as areas that are heavily vegetated or forested. More localized acidic conditions include pipes subject to mine runoff, heavily fertilized areas, and soils rich in organic matter.

- Microbiological (anaerobic) corrosion: Anaerobic corrosion generally occurs in low-lying areas with brackish waters. The soils where this is prevalent include poorly drained clays, silty clays, peats, and mucks with organic material. Soils are almost always saturated or moist, and sulfides are generally present. Swampy/marshy areas are excellent breeding grounds (Gabriel and Moran 1998). Known areas where this has caused rapid deterioration include, but are not limited to, large parts of Wisconsin; coastal areas of Michigan; Florida Everglades; areas of northwest Arkansas and northeast Mississippi with saturated, organic, silt/clay; and areas with saturated silt/clay in north-central Utah and central New York (Horton et al. 2006 and Kroon et al. 2004).

- Chloride corrosion: Corrosive soils/waters are often the result of the presence of chlorides. Sources of these chlorides vary but include coastal environments, areas that are heavily fertilized, areas that heavily use de-icing salt during winter, highly industrialized areas, or areas that were once covered by or exposed to salt water. In addition, arid regions often have high chloride levels in the soil because of low rainfall amounts since rainfall tends to leach chlorides out of the soil.

- Damaging soils: Generally, the most damaging soils tend to be mucks, marshes, peats, cinders, fat clays, and those with organic content. Those that are subjected to frequent fluctuations of moisture and that do not drain freely are problematic. Clays with high swell potential are considered extremely corrosive. The map of swelling clays (https://doi.org/10.3133/i1940) published by the USGS (Olive et al. 1989) can help assess the potential for expansive clays when site-specific data is unavailable. Soils with sulfate levels exceeding 150 ppm, though rare, are also extremely corrosive. These soils typically have very low resistivity values of less than 2,000 ohm-centimeters (Ω-cm) (Gabriel and Moran 1998).

Aggressive deterioration environments for aluminum-coated Type 2 CSP (ALCLAD® or equivalent) differ slightly from the other two pipe materials. The previously described aggressive deterioration environments for microbiological (anaerobic) corrosion and damaging soils apply, along with the following:

- Extremely acidic conditions: Soil or water that is extremely acidic (pH less than 4) can cause rapid deterioration. Areas where this is likely are localized and typically associated with an external factor such as acidic mine runoff or other phenomenon causing extremely acidic conditions (Gabriel and Moran 1998).

- Extreme alkaline conditions: Soil or water that is extremely alkaline (pH greater than 10) can cause rapid deterioration. This situation is uncommon, but it does occur in very arid regions of the western United States.

For the chosen pipe material, select the number of aggressive deterioration environments that are applicable or likely applicable using the drop-down list. The options include None, One, or Multiple. Based on the pipe material and number of aggressive deterioration environments, the deterioration environment for the pipe is characterized as mild, aggressive, or extremely aggressive using Table 6, which applies to both CSP and CAP.

Table 6
Deterioration environment.

Flow Velocity	Deterioration Environment		
	None	One	Multiple
Non-Abrasive	Mild	Aggressive	Extremely Aggressive
Abrasive	Aggressive	Extremely Aggressive	Extremely Aggressive
Extremely Abrasive	Extremely Aggressive	Extremely Aggressive	Extremely Aggressive

5.7. Pipe Wall Thickness

Step 7 assessed the pipe wall thickness. Commonly, plans only show the pipe gage and/or diameter. Using the drop-down list, select Yes if the pipe wall thickness is known, or No if the pipe wall thickness is unknown. For Yes, specify the pipe wall thickness as illustrated in Figure 19. For No, choose the

method of estimating the pipe wall thickness using the drop-down list. The methods include Gage and Diameter. For Gage, choose the pipe gage, and the pipe wall thickness is estimated using a pipe gage and pipe schedule as illustrated in Figure 20. When using the pipe gage schedule, if the pipe wall thicknesses from both schedules are not consistent, use the thinner pipe wall thickness. For Diameter, specify the pipe diameter, and the pipe wall thickness is estimated using a pipe diameter schedule as illustrated in Figure 21. Cells that do not apply have a gray background.

Step 7: Assess the pipe the wall thickness

Is the pipe wall thickness known?   Yes

Pipe wall thickness, t   0.052 in

Figure 19. Step 7 of Steel and Aluminum Pipe worksheet: User-specified pipe wall thickness.

Step 7: Assess the pipe the wall thickness

Is the pipe wall thickness known?   No

Pipe wall thickness, t   0.052 in

Use the applicable pipe schedule below. If using the pipe gage schedule, if the pipe wall thickness from both schedules are not consistent, use the thinner pipe wall thickness.

Method for estimating pipe diameter   Gage

Gage	Wall Thickness			Diameter	Wall Thickness		
	(in)	(mm)		(in)	(in)	(mm)	
18	0.052	1.32		≤ 8	0.052	1.32	
16	0.064	1.63		8 < D ≤ 24	0.064	1.63	
14	0.079	2.10		24 < D ≤ 36	0.079	2.10	
12	0.109	2.77		36 < D ≤ 54	0.109	2.77	
10	0.138	3.51		54 < D ≤ 72	0.138	3.51	
8	0.168	4.27		D > 72	0.168	4.27	

Pipe gage   14   Pipe diameter, D   3 in
Pipe wall thickness, t   0.079 in   Pipe wall thickness, t   0.052 in

Use pipe wall thickness, t   0.052 in

Figure 20. Step 7 of Steel and Aluminum Pipe worksheet:
Pipe wall thickness using pipe gage schedule

**Figure 21. Step 7 of Steel and Aluminum Pipe worksheet:
Pipe wall thickness using pipe diameter schedule.**

5.8. Pipe Material Loss Rate

In step 8, the material loss rate (r_m) for steel and aluminum pipe is estimated based on the base metal type, flow likelihood, and deterioration environment as illustrated in Table 7 and Table 8. The pipe material loss rates (inches per year) were developed by synthesizing several studies in a wide range of operating environments including, but not limited to, Ault and Ellor (2000), Bednar (1989), Bellair and Ewing (1984), DeCou and Davies (2007), Gabriel and Moran (1998), Idaho Department of Highways (1965), Jacobs (1982), Kill (1969), Malcom (1993), Meacham et al. (1982), Missouri Highway and Transportation Department (1990), Potter et al. (1991), and Summerson and Hogan (1979).

This step has no user-specified input. Cells that do not apply have a gray background.

Table 7
Material loss rate for traditional galvanized CSP and aluminum-zinc alloy-coated CSP (Galvalume® or equivalent).

Flow Likelihood	Material Loss Rate, r_m (in/yr)		
	Extremely Aggressive	Aggressive	Mild
Likely	0.0130	0.0028	0.00066
Unlikely	0.0055	0.0014	0.00036

Table 8
Material loss rate for aluminum-coated Type 2 CSP (ALCLAD® or equivalent).

Flow Velocity	Material Loss Rate, r_m (in/yr)		
	Extremely Aggressive	Aggressive	Mild
Likely	0.0178	0.00072	0.00019
Unlikely	0.0089	0.00036	0.00014

5.9. External Corrosion Protection System

Step 9 assesses the effectiveness of the external corrosion protection system on the pipe. Select the type of external corrosion protection system using the drop-down list. Bituminous (asphalt) coating, bituminous coating with paved invert, fiber-bonded and bituminous coating, concrete-lined, coal tar base resin (Nexon™ or equivalent), polyvinyl chloride plastisol (Beth-Cu-Loy™ or equivalent), ethylene acrylic acid film, epoxy coating can be evaluated. Select None if no external corrosion protection system exists. The galvanized zinc coating that is typically applied to a CSP as part of the manufacturing process is not considered an external corrosion protection system.

The additional service life (*A*) is obtained from a table as a function of relative flow abrasiveness as illustrated in Figure 22. For extremely abrasive flow conditions, external corrosion protection systems are quickly worn away and do not provide additional years of service with respect to material loss rates (Potter et al. 1991 and DeCou and Davies 2007). Similar to the evaluations of material loss rates for pipes, there are numerous studies investigating the effectiveness of external corrosion protection systems on drainage pipes. Studies by Bonds et al. (2005), Potter et al. (1991), Gabriel and Moran (1998), and DeCou and Davies (2007) were some of the evaluations used to develop the additional years of service life for external protection systems in this toolbox.

For Other, specify the additional service life as illustrated in Figure 23. Specified values must have supporting documentation by an independent study, not a study conducted by or sponsored by the manufacturer. The specified additional service life must be inversely proportional to the relative flow abrasiveness (as the relative abrasiveness increases, the additional service life must decrease).

Step 9: Assess the effectiveness of the external corrosion protection system

External corrosion protection system   Bituminous (asphalt) coating
External corrosion protection system

External Corrosion Protection System	Additional Service Life (yr)		
	Extremely Abrasive	Abrasive	Non-Abrasive
Bituminous (asphalt) coating	0	3	8
Bituminous coating with paved invert	0	5	15
Fiber-bonded and bituminous coating	0	10	30
Concrete lining over bituminous coating	0	5	30
Coal tar base resin (Nexon™ or equivalent)	0	2	7
Polyvinyl chloride plastisol (Beth-Cu-Loy™ or equivalent)	0	2	9
Ethylene acrylic acid film (EAAF)	0	10	30
Epoxy coating	0	0	0
None	0	0	0
Other			

Note: User-specified values must have supporting documentation by an independent study, not a study conducted by or sponsored by the manufacturer.

Additional service life, A   8 years

Figure 22. Step 9 of Steel and Aluminum pipe worksheet: Material loss rate.

Step 9: Assess the effectiveness of the external corrosion protection system

External corrosion protection system   Other
External corrosion protection system   XYZ

External Corrosion Protection System	Additional Service Life (yr)		
	Extremely Abrasive	Abrasive	Non-Abrasive
Bituminous (asphalt) coating	0	3	8
Bituminous coating with paved invert	0	5	15
Fiber-bonded and bituminous coating	0	10	30
Concrete lining over bituminous coating	0	5	30
Coal tar base resin (Nexon™ or equivalent)	0	2	7
Polyvinyl chloride plastisol (Beth-Cu-Loy™ or equivalent)	0	2	9
Ethylene acrylic acid film (EAAF)	0	10	30
Epoxy coating	0	0	0
None	0	0	0
Other	0	2	5

Note: User-specified values must have supporting documentation by an independent study, not a study conducted by or sponsored by the manufacturer.

Additional service life, A   5 years

Figure 23. Step 9 of Steel and Aluminum pipe worksheet: User-specified additional service life.

5.10. Remaining Service Life

Step 10 calculates the remaining service life for the pipe as illustrated in Figure 24, both with and without external protection. The service life without external protection (L_o) is calculated by dividing the pipe wall thickness (t) by the material loss rate (r_m). The service life with external protection (L) is calculated by adding the additional service life due to the external protection system (A) to the service life without external protection (L_o).

Specify the number of years in service (N). The remaining service life (T) is calculated by subtracting the number of years of service (N) from the service life (L). If the remaining service life is less than or equal to 5 years, the cell has an orange background. A negative remaining service life is the number of years exceeding the service life.

If the remaining service life is greater than 5 years, the pipe condition is likely satisfactory. If the remaining service life is greater than or equal to -5 years and less than or equal to 5 years, the pipe is likely near the end of service life. If the remaining service life is less than -5 years, the pipe has likely exceeded service life.

Step 10: Estimate the remaining service life	
Service life without external protection, $L_o = t / r_m$	273.7 years
Service life with external protection, $L = L_o + A$	281.7 years
Number of years in service, N	47.0 years
Remaining service life, $T = L - N$	234.7 years
Conclusion: Pipe condition is likely satisfactory.	

Figure 24. Step 10 of Steel and Aluminum Pipe worksheet: Remaining service life.

6. Concrete Pipe

Reinforced concrete pipes (RCP) are commonly used to convey interior drainage through levee embankments and floodwalls. This worksheet applies to traditional gravity drainage structures made from either precast or cast-in-place concrete. This worksheet does not apply to large conduits that convey water from a reservoir through, under, or around an embankment dam in a controlled manner.

6.1. Pipe Shape Characterization

The pipe shape characterization is the same as steel and aluminum pipe. For Arch, choose the pipe arch size based on ASTM C506 using the drop-down list, and the equivalent diameter displays as illustrated in Figure 25. For Other, specify the description of the pipe arch size and equivalent diameter as illustrated in Figure 26. Cells that do not apply have a gray background.

Figure 25. Step 1 of Concrete Pipe worksheet: Arch pipe dimensions.

Figure 26. Step 1 of Concrete Pipe worksheet: User-specified arch pipe dimensions.

6.2. Flow Velocity Characterization

The pipe shape characterization is the same as steel and aluminum pipe. A Manning's roughness coefficient (n) of 0.012 is suggested for smooth concrete as an interior flow surface (USACE 2020).

6.3. Flow Frequency Characterization

The flow frequency characterization is the same as steel and aluminum pipe.

6.4. Bedload Characterization

The bedload characterization is the same as steel and aluminum pipe.

6.5. Flow Abrasiveness Characterization

The flow abrasiveness characterization is the same as steel and aluminum pipe.

6.6. Deterioration Environment Characterization

Step 6 characterizes the aggressive deterioration environment. Aggressive deterioration environments for concrete include extremely acidic conditions, microbiological (anaerobic) corrosion, and chloride corrosion (Potter 1988). These environments are the same as steel and aluminum pipe. Additional aggressive deterioration environments for RCP include the following:

- Freeze/thaw damage: Two concerns when assessing the potential for this type of damage are air entrainment and temperature environment. If the concrete pipe was constructed before 1945, it likely did not include air entrainment in the concrete mix design. If the pipe is likely not air-entrained and is located in a region that has considerable freeze/thaw cycles, freeze/thaw damage is considered likely unless other information is available. Climatic data, such as the map of annual freeze/thaw cycles (https://doi.org/10.1175/1520-0450(1974)013%3C0348:TFOFTC%3E2.0.CO;2) published by Hershfield (1974), can help assess the potential for damaging freeze/thaw cycles. Over 120 annual freeze/thaw cycles represent an aggressive deterioration environment without air entrainment and no known existing signs of cracking or distress. If there is any historic evidence of even minor cracking or distress in the pipe, over 80 annual freeze/thaw cycles are considered aggressive for a non-air-entrained RCP.

- Chemical attack: Two types of chemical attack concerns are sulfate attack and alkali-silica reaction. Sulfate attack can occur when the soil, water, or effluent has a sulfate level that exceeds 1,000 ppm (Potter 1988). This generally occurs in arid regions when the soil is very alkaline (pH greater than or equal to 9). Damage is more likely on structures that are partially buried, as opposed to those fully buried, due to capillary action and surface evaporation. If Type II or Type V Portland cement is not used, sulfate damage is likely. Sulfate levels are generally high in areas with expansive clays and/or gypsum. Highly alkaline soils are primarily present in arid, western portions of the U.S. The second type of chemical attack is alkali-silica reaction (ASR). ASR occurs when there is a chemical reaction between the aggregate and cement used in the concrete mix. This causes the concrete to expand, eventually suffer cracking/distortion, and structurally weaken. While rare for pipes, it has been known to cause RCP failures (Haavik and Mielenz 1991).

Select the number of aggressive deterioration environments that are applicable or likely applicable using the drop-down list. The options include None, One, or Multiple. Based on the pipe material and number of aggressive deterioration environments, the characterization of the deterioration environment for the pipe is the same as for steel and aluminum pipe.

6.7. Remaining Service Life

Step 7 calculates the remaining service life for the pipe. The service life is obtained from a table as a function of flow likelihood and deterioration environment as illustrated in Figure 27.

Specify the number of years in service (N). The remaining service life (T) is calculated by subtracting the number of years of service (N) from the service life (L). If the remaining service life is less than or equal to 5 years, the cell has an orange background. A negative remaining service life is the number of years exceeding the service life.

Step 7: Estimate the remaining service life

Flow Likelihood	Service Life (yr)		
	Extremely Aggressive	Aggressive	Mild
Likely	30	50	100
Unlikely	40	75	300

Service life, L	50.0	years
Number of years in service, N	47.0	years
Remaining service life, T = L – N	3.0	years

Figure 27. Step 7 of Concrete Pipe worksheet: Remaining service life.

The remaining service life characterization is the same as steel and aluminum pipe.

7. Iron Pipe

Ductile and cast iron pipes are most often associated with utility distribution systems for water supply, gas lines, etc. The primary difference between the two types of iron is metallurgy. Cast iron has small flakes of graphite, but ductile iron contains spherical graphite nodules that make it more durable and malleable. Ductile iron, as its name implies, is a flexible material, whereas cast iron is more brittle. Cast iron has been around for centuries, but ductile iron first saw commercial use in the mid-20th century. Due to its brittle nature, cast iron pipes typically are much thicker than ductile iron pipes of the same inside diameter.

The performance of iron pipes is generally controlled by external corrosion, since abrasive bedloads are usually not present. Metal loss rates where abrasive conditions are not a concern are a function of external corrosion. Ductile iron pipes, which largely replaced cast iron pipes in water distribution systems in the 1970s, are similar to thicker galvanized steel pipes in terms of external corrosion.

Some projects may use ductile or cast iron pipes as gravity drainage structures. If this occurs, evaluate the pipe as a steel pipe using the Steel and Aluminum Pipe worksheet, but with the modified thickness for the iron. The Iron Pipe worksheet applies only to utility distribution pipes that are pressurized with no bedload present.

7.1. Pipe Material

In Step 1, select the applicable type of iron material using the drop-down list, as illustrated in Figure 28. The two choices are ductile iron or cast iron.

Figure 28. Step 1 of Iron Pipe worksheet: Pipe type.

If the iron type is unknown, the installation period may offer a clue. If installed before 1970, the pipe is likely cast iron. If installed after 1980, the pipe is likely ductile iron. The 1970s were a transition period for the industry where both types of pipes were commonly used. If the pipe was installed sometime in the 1970s, use the ductile iron pipe wall thickness for the evaluation, since it is a more conservative approach to the evaluation due to ductile iron pipe having thinner walls.

7.2. Pipe Wall Thickness

Step 2 assesses the pipe wall thickness. If the pipe wall thickness is known, select Yes using the drop-down list and specify it as shown in Figure 29. If the pipe wall thickness is not known, select No using the drop-down list to obtain the pipe wall thickness from the pipe schedule based on the pipe type (from step 1) and the user-specified pipe diameter, as illustrated in Figure 30. The wall thicknesses in Figure 30 were adapted from Cast Iron Pipe Research Association (CIPRA) (1927) and Ductile Iron Pipe Research Association (DIPRA) (2016) for ductile iron pipe and cast iron pipe, respectively.

Step 2: Assess the pipe the wall thickness

Is the pipe wall thickness known?   Yes

Pipe wall thickness, t   0.052 in

Use the pipe schedule below to obtain the pipe diameter.

Diameter (in)	Wall Thickness (in)	
	Ductile Iron	Cast Iron
D ≤ 10	0.25	0.50
10 < D ≤ 14	0.27	0.60
14 < D ≤ 20	0.34	0.70
20 < D ≤ 24	0.38	0.85
24 < D ≤ 30	0.42	0.95
30 < D ≤ 36	0.47	1.10
36 < D ≤ 42	0.52	1.20
42 < D ≤ 48	0.58	1.35
48 < D ≤ 54	0.65	1.50
54 < D ≤ 60	0.68	1.60
60 < D ≤ 72	0.72	1.85
D > 72	0.80	2.20

Pipe diameter   36 in
Pipe wall thickness, t   #N/A in

Use ductile pipe wall thickness, t   0.052 in

Figure 29. Step 2 of Iron Pipe worksheet: User-specified pipe wall thickness.

Figure 30. Step 2 of Iron Pipe worksheet: Pipe wall thickness using pipe diameter schedule.

7.3.   Corrosive Environment Characterization

Step 3 characterizes the corrosive environment. The first part of step 3 assesses the presence of very corrosive environments due to stray electrical current, extremely acidic (pH less than 4) conditions, microbiological (anaerobic) corrosion, chloride corrosion, or damaging soils. These environments are the same as steel and aluminum pipe. If any of these very corrosive environments are applicable or likely applicable, select Yes as illustrated in Figure 31. Otherwise, select No.

Figure 31. Step 3 of Iron Pipe worksheet: Very corrosive environment characterization.

The second part of step 3 assesses the presence of corrosive environments due to highly acidic conditions and moderately corrosive soils, which include the following:

- Highly acidic conditions: Soil or water that is very acidic (pH between 4 and 5) is known to corrode metal rapidly. Acidic conditions are fairly widespread in areas east of the Mississippi River due to industrialization, acidic rainfall, and heavily vegetated areas. If the soil, water, or effluent around or flowing through the pipe is extremely acidic (pH < 4), assess it as very corrosive.

- Moderately corrosive soils: Soils considered corrosive (but not very corrosive) include lean clays, loess, silts, and silty clay/clayey silt mixtures with low resistivity values (2,000 to 5,000 Ω-cm), but not as extreme as very corrosive soils (Gabriel and Moran 1998, Kroon et al. 2004, and Potter 1988).

If any of these corrosive environments are applicable or likely applicable, select Yes using the drop-down list as illustrated in Figure 32. Otherwise, select No.

Corrosive Environments

Are any of the corrosive environments listed below applicable   Yes
or likely to be applicable for the pipe being evaluated?

Figure 32. Step 3 of Iron Pipe worksheet: Corrosive environment characterization.

If Yes was selected from the first drop-down list, a very corrosive environment exists or is likely to exist. If No was selected from the first drop-down list (very corrosive environment does not exist or is unlikely to exist) and Yes was selected from the second drop-down list, a corrosive environment exists or is likely to exist. If No was selected from both drop-down lists, the corrosive environment is characterized as mild.

7.4. Pipe Material Loss Rate

Step 4 assesses the external pipe material loss rate (r_m), as illustrated in Figure 33. Select the corrosion protection applied to the exterior surface of the iron pipe using the drop-down list. The three options are Polyethylene encasement, Bituminous coating, or None. The material loss rate is obtained using a lookup table based on the corrosive environment (from step 3) and the user-specified external corrosion protection. The pipe material loss rates (inches per year) were developed by synthesizing several studies in a wide range of operating environments including, but not limited to, Kroon et al. (2004), Bonds et al. (2005), Gabriel and Moran (1998), DIPRA (2017), and Szeliga and Simpson (2003).

Step 4: Assess the pipe material loss rate

External corrosion protection   Polyethylene encasement

External Corrosion Protection	Material Loss Rate, r_m (in/yr)		
	Very Corrosive	Corrosive	Mild
Polyethylene encasement	0.0068	0.000453	0.000001
Bituminous coating	0.0287	0.0105	0.000667
None	0.0442	0.0151	0.000959

Material loss rate, r_m 0.0068 in/yr

Figure 33. Step 4 of Iron Pipe worksheet: Pipe material loss rate.

7.5. Remaining Service Life

The service life of the pipe is calculated as the original pipe wall thickness (t) divided by the material loss rate (r_m). Specify the number of years in service (N).

The remaining service life (T) is calculated by subtracting the number of years in service (N) from the service life (L). If the remaining service life is less than or equal to 5 years, the cell has an orange background. A negative remaining service life is the number of years exceeding the service life. The calculation is illustrated in Figure 34.

Step 5: Estimate the remaining service life	
Service life, $L = t / r_m$	69.1 yr
Number of years in service, N	47.0 yr
Remaining service life, $T = L - N$	22.1 yr

Figure 34. Step 5 of Iron Pipe worksheet: Remaining service life.

The remaining service life characterization is the same as steel and aluminum pipe.

8. Plastic Pipe

Plastic pipes through or beneath a levee embankment or floodwall usually consist of a thermoplastic material. The most commonly used thermoplastic pipes are high-density polyethylene (HDPE), polypropylene (PP), and polyvinyl chloride (PVC). Other plastic pipe materials may exist, but for the purposes of this toolbox, they are all considered generically as plastic pipe.

8.1. Pipe Condition

Plastic pipe has performed well in many environments that are corrosive to metal and concrete pipes. Plastic pipes are also more abrasion resistant compared to metal pipes (Potter 1988). The exception to this is very abrasive conditions, where long-term performance of plastic pipes is not well defined.

The greatest concern with plastic pipe is deformation leading to damage at the joints or other sections of the pipe. This was verified by at least two field studies of HDPE pipe by Gassman et al. (2005) and Nelson and Krauss (2002). Both studies showed evidence of major problems with the joints from excessive deflection and/or differential movement of the pipe.

In step 1, the condition of the plastic pipe is verified using a drop-down list, as illustrated in Figure 35. Select Yes if a recent inspection (within 5 years) confirms no excessive deflections (more than 5 percent of the pipe diameter) or offsets or bulges along the pipe. Select No if it is positively identified that those conditions do not exist.

Step 1: Characterize the pipe condition	
Does a recent inspection (i.e., within 5 years) confirm the deflection of the pipe is less than 5% of the pipe diameter and no signs of offsets or bulges along the pipe?	Yes

Figure 35. Step 1 of Plastic Pipe worksheet: Pipe condition.

8.2. Remaining Service Life

Since less is known about the long-term performance of plastic pipes in levee and floodwall applications compared to other materials (steel, aluminum, concrete, etc.), a default service life is assumed to be 50 years based on work done by Potter (1988).

The selection in step 1 affects the service life in step 2. If Yes was selected in step 1, the service life (L) of the plastic pipe is assumed to be 50 years. If No was selected in step 1, L is 0 years (the pipe has failed). Specify the number of years in service (N).

The remaining service life (T) is calculated by subtracting the number of years of service (N) from the service life (L). If the remaining service life is less than or equal to 5 years, the cell has an orange background. A negative remaining service life service life is the number of years exceeding the service life. The calculation is illustrated in Figure 36.

Step 2: Estimate the remaining service life

If a recent inspection confirms there are no excessive deflections (more than 5% of the pipe diameter) or offsets or bulges along the pipe, the service life is assumed to be 50 years. Otherwise, the pipe is assumed to have failed, and the service life is zero.

Service life, L	50.0	yr
Number of years in service, N	47.0	yr
Remaining service life, T = L − N	3.0	yr

Figure 36. Step 2 of Plastic Pipe worksheet: Remaining service life.

The remaining service life characterization is the same as steel and aluminum pipe.

9. Clay Pipe

Clay pipes have been used in sanitary sewer systems for thousands of years. There are two types of clay pipes. Older clay pipes (placed in service prior to the late 1970s to early 1980s) are likely terracotta (literally meaning "baked earth"). Terracotta is a dried clay fired to 1,200°F. Any clay pipe placed in service since the early 1980s is likely vitrified clay pipe (VCP). Vitrified clay is a ceramic fired to over 2,000°F. Vitrification significantly increased the density and mechanical bonding properties of the pipe's particles when compared to terracotta, making it more durable and less susceptible to breakage.

9.1. Pipe Condition

Clay pipes are highly resistant to very abrasive and corrosive environments (Gabriel and Moran 1998 and Potter 1988). The greatest concerns with clay pipes are deformation, deflection, or misalignment. This is especially true for older terracotta clay pipes. Differential movement and/or settlement can cause a separation of the joints or breakage of the brittle pipe. Clay pipes are typically provided in very short lengths (2 to 4 feet) due to their weight. Therefore, clay pipes usually have more joints relative to other pipe materials, making them potentially more susceptible to joint performance issues. Another concern with clay pipes is the potential for tree roots to penetrate the body of the pipe or open the joints.

Step 1 assesses the condition of the pipe, as illustrated in Figure 37. Using the drop-down list, select Yes if a recent inspection (within 5 years) confirms no deformations, signs of deflection, or joint openings along the pipe. Select No if the condition is unknown or those conditions are known to exist.

Figure 37. Step 1 of Clay Pipe worksheet: Pipe condition.

9.2. Remaining Service Life

Because clay pipes are highly resistant to very abrasive and corrosive environments, many municipal sewer inspections reveal clay pipes in very good condition and functioning as designed, despite being over 100 years old. Therefore, service life by itself is not necessarily the best indicator of performance.

The selection in step 1 affects the service life in step 2. If Yes was selected in step 1, the service life (L) of the clay pipe is assumed to be 100 years (Potter 1988). If No was selected in step 1, L is 0 years (the pipe has failed). Specify the number of years in service (N).

The remaining service life (T) is calculated by subtracting the number of years of service (N) from the service life (L). If the remaining service life is less than or equal to 5 years, the cells have an orange background. A negative remaining service life is the number of years exceeding the service life. The calculation is illustrated in Figure 38.

Step 2: Estimate the remaining service life

If a recent inspection confirms there are no deformations, signs of deflection, or joint openings along the pipe, the service life is assumed to be 100 years. Otherwise, the pipe is assumed to have failed, and the service life is zero.

Service life, L	100.0 yr
Number of years in service, N	47.0 yr
Remaining service life, T = L − N	53.0 yr

Figure 38. Step 2 of Clay Pipe worksheet: Remaining service life.

The remaining service life characterization is the same as steel and aluminum pipe.

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Appendix A. Acronym List

ASR	Alkali Silica Reaction
CAP	Corrugated Aluminum Pipe
CIPRA	Cast Iron Pipe Research Association
CPD	Computer Program Document
CSP	Corrugated Steel Pipe
DC	Direct Current
DIPRA	Ductile Iron Pipe Research Association
HDPE	High-Density Polyethylene
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
PP	Polypropylene
PVC	Polyvinyl Chloride
QC	Quality Control
RCP	Reinforced Concrete Pipe
RMC	Risk Management Center
UDF	User-Defined Function
U.S.	United States
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VCP	Vitrified Clay Pipe