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MONASH University Civil Engineering

User Manual
Module 2 – Pipe failure analysis

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INTRODUCTION

The pipe failure analysis module[1], previously known as the Monash Tool (MT), was developed by the Monash Infrastructure Doctors in the Advanced Condition Assessment and Pipe Failure Prediction (ACAPFP) project to facilitate longitudinal failure analysis of buried cast iron pipe barrels with uniform corrosion and/or single corrosion defects that are idealised into ellipsoids. It should be noted that this pipe failure analysis module was originally developed for cast iron pipes only and care should be taken when it is used for analysing steel pipes.

The pipe failure analysis module consists of the following two sub-modules (Figure 1):

a) Module 1: **Time to Failure module**, and

b) Module 2: **Lifetime Probability of Failure module**

Figure 1. Overview of the pipe failure analysis module

1 TIME TO FAILURE

Given pipe and soil properties, loading and corrosion patch geometry, the Time to Failure module is capable of predicting the actual hoop (maximum) tensile stress in the pipe. Given corrosion rates, the Time to Failure module can predict the time window from current pipe condition to when a failure occurs. The Time to Failure module also determines the type of failure (leak or burst) caused by corrosion. When a leak rather than a burst occurs, the Time to Failure module allows the user to further assess the potential burst failure of corroded cast iron pipes caused by pressure transients and determines the time window for leak before break. The Time to Failure module also incorporates the analysis of uncertainty of key physical parameters and predict the probability of failure and hazard rate over the specified number of years.

Based on the sensitivity analysis conducted by Ji et al. (2017), the key parameters that play a dominant role on pipe performance, include pipe internal diameter, pipe wall thickness, the corrosion model, the corrosion patch dimensions and the maximum allowable pressure applied to the pipe.

1.1 Pipe stress analysis

1.1.1 Input pipe parameters

The input parameters for pipe and soil properties and loading conditions are shown in Figure 2.

[1] The “User manual for Pipe failure analysis module” currently only includes the Monash Tool for condition evaluation of cast iron pipes. The failure history, deterioration rate and leak rate methods used for AC and metallic pipe condition evaluation are included in the “User manual for Liner selection module”.

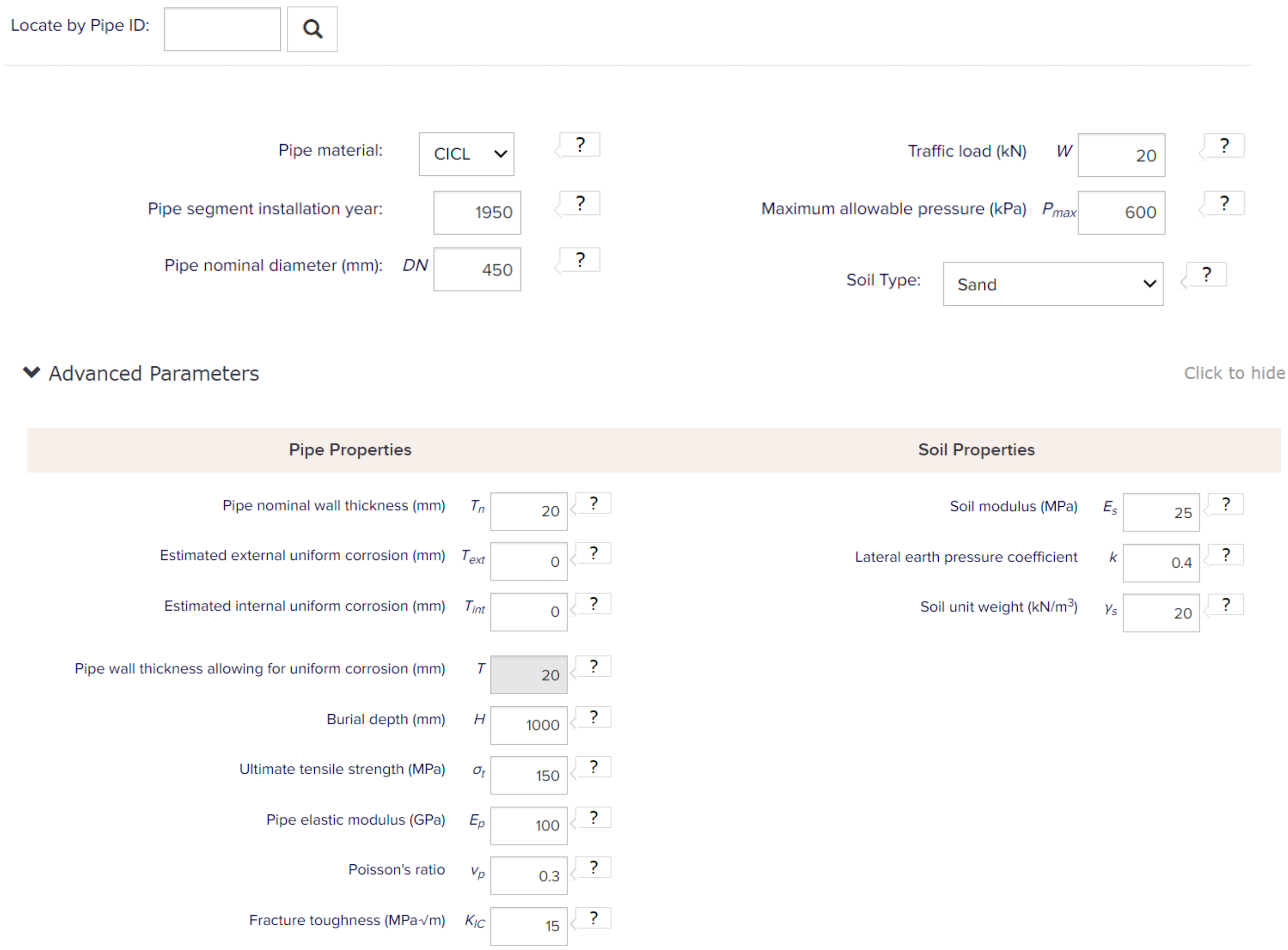


Figure 2. Input parameters for pipe and soil properties and loading

- **Pipe material**: Host pipe material type. This includes metallic pipes, cement pipes, plastic pipe, etc. As the Time to Failure modulus was originally developed for cast iron pipes only and may be applied to steel pipes, users can select either “Cast Iron” or “Steel” from the drop-down list.
- **Pipe segment installation year**: Construction year of the pipe, burial year of the pipe or pipe installation year. The pipe segment installation year is used to gather cohort properties about the pipe when the geometrical and/mechanical properties of the pipe material is unknown/unavailable.
- **Pipe nominal diameter DN**: the Nominal diameter of the pipe or internal diameter of the pipe. Typically, the nominal diameter is expressed in mm conveniently rounded to roughly the manufactured internal diameter, however the imperial terms use inches. A DN150 pipe has an internal diameter of 150 mm (Imperial, DN6 is 6 inch). Nominal diameter can be used as an approximate for internal diameter (D) if internal diameter is unknown. Otherwise, cohort values can be used to determine the host pipe internal and external diameters.
- **Traffic load W:** indicated by the wheel load applied on the ground surface (Figure 5). Units are in kN. $\mathbf{0 \le W}$. The wheel load represents a single tyre load from traffic (e.g., steering axle). For other axles with multiple tyres, it is necessary to estimate an appropriate single tyre load. See Table 2 for recommendations. Note that for a pipe buried at a depth of more than 800 mm, the effect of the traffic load on the maximum stress in the pipe is negligible.
- **Maximum allowable pressure P_{max}:** the maximum pressure applied to the pipe, which equals to the sum of the operating pressure and the surge pressure (Figure 3). Units are in kPa.

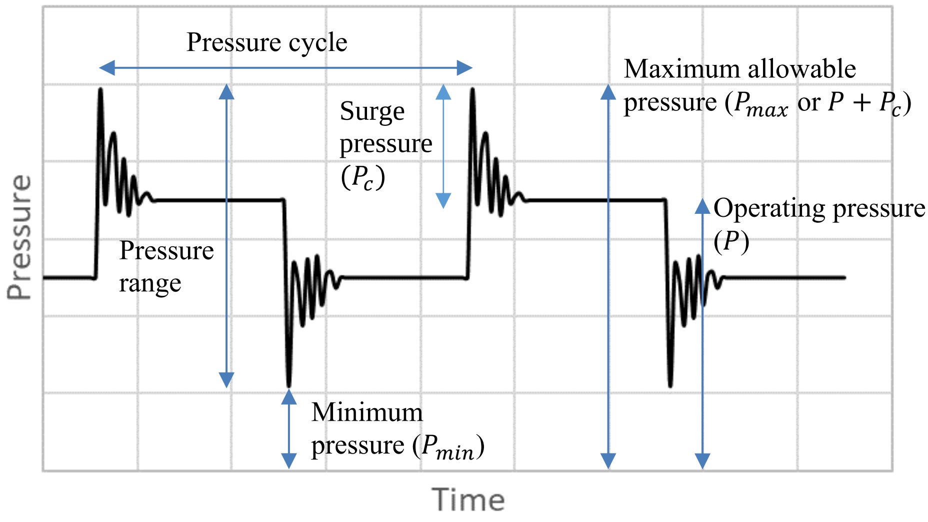


Figure 3. Types of pressures

- **Soil type:** Soil type could be any of the following soils: sand, loamy sand, sandy loam, fine sandy loam, loam, silty loam, sandy clay loam, fine sandy clay loam, clay loam, silty clay loam, sandy clay, light clay, silty clay, medium clay, heavy clay. The soil type names are from AS 4419 (2018). The users can select a soil type from the list and the soil properties will be prefilled.
- **Pipe nominal wall thickness $\boldsymbol{T_n}$**: the original wall thickness of the pipe (Figure 4). Units are in mm. $T_n > 0$.
- **Estimated external uniform corrosion $\boldsymbol{T_{ext}}$**: the pipe wall thickness reduction caused by external corrosion (Figure 4). Units are in mm. $0 < T_{ext} < T_n$.
- **Estimated internal uniform corrosion $\boldsymbol{T_{int}}$**: the pipe wall thickness reduction caused by internal corrosion (Figure 4). Units are in mm. $0 < T_{int} < T_n - T_{ext}$.
- **Pipe wall thickness allowing for uniform corrosion $\boldsymbol{T}$**: the actual pipe wall thickness after accounting for external and internal corrosion (Figure 4). Units are in mm. Note that $\boldsymbol{T = T_n - T_{ext} - T_{int}}$.

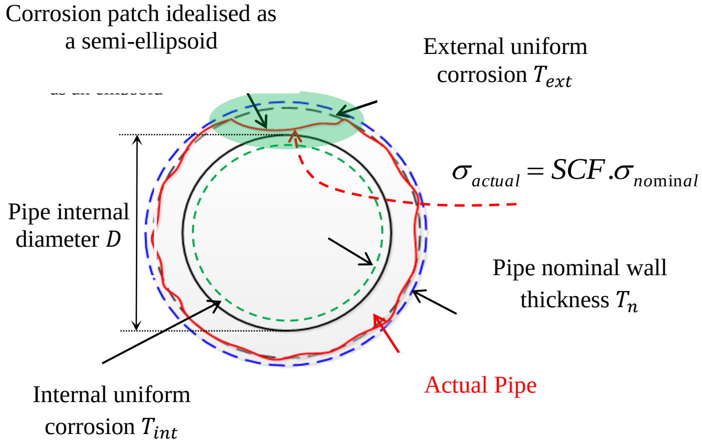


Figure 4. Cross section of a corroded pipe

- **Burial depth $\boldsymbol{H}$**: the depth of the pipe from the ground surface level to the crown of the pipe (Figure 5). Conservatively, the pavement structure is not specifically represented. It may be possible to use a height weighted average soil modulus, if the influence of pavement is essential. Units are in mm. $0 \leq H$.

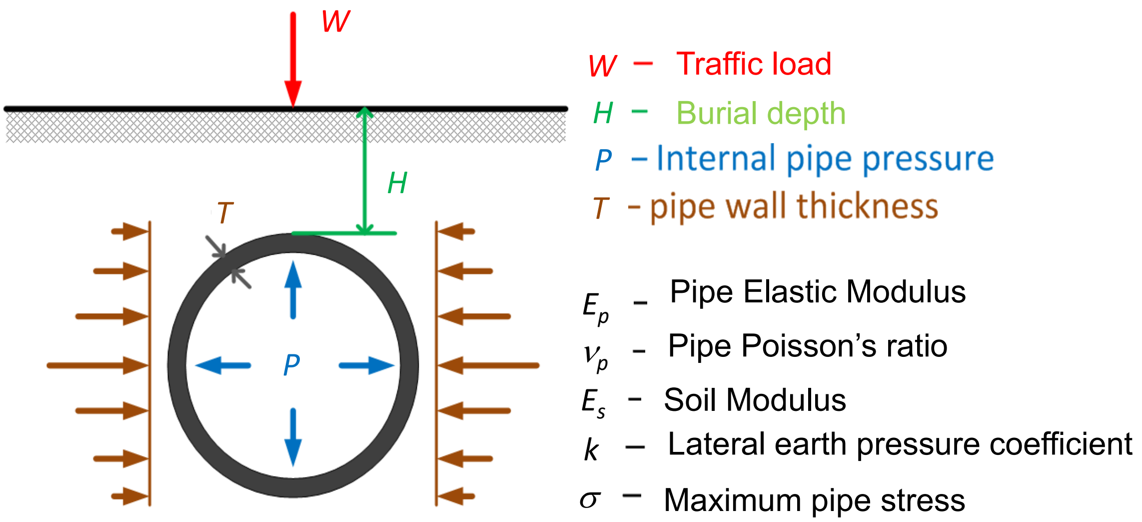


Figure 5. General variables for a buried cast iron pipe

- **Ultimate tensile strength $\boldsymbol{\sigma_t}$**: the maximum stress that a material can withstand while being stretched or pulled before breaking. Units are in MPa. $0 < \boldsymbol{\sigma_t}$.
- **Pipe elastic modulus $\boldsymbol{E_p}$**: also known as Young's modulus or modulus of elasticity, it is the slope of stress–strain curve in the elastic deformation region for the pipe material. Units are in GPa. Note that for cast iron material, $50 \leq E_p \leq 150$ GPa while for steel material, $190 \leq E_p \leq 210$ MPa. Note: Care should be taken when the Pipe Failure Analysis module is used for steel pipes.
- **Poisson's ratio $\boldsymbol{v_p}$:** the measurement of deformation in pipe material in a direction perpendicular to the direction of the applied force. Units are dimensionless. Note for cast iron, $0.21 \leq v_p \leq 0.26$ while for steel, $0.27 \leq v_p \leq 0.3$.
- **Fracture toughness $\boldsymbol{K_{IC}}$**: the resistance of materials to the propagation of cracks under an applied stress. Units are in $\mathrm{MPa}\sqrt{m}$. $0 < \boldsymbol{K_{IC}}$. Fracture toughness testing should be conducted on specimens cut from the cast iron pipe, following ASTM E399 (2019), to determine the fracture toughness value. If no testing is conducted, then Table 1 may be used given that the pipe manufacturing technique is known.

Table 1. Fracture toughness values for cast iron (Kodikara 2018)

	PIT-H	PIT-V	SPUN-I	SPUN-D	SPUN-S	SPUN-Y
Fracture Toughness ($\mathrm{MPa}\sqrt{\mathrm{m}}$)	9.1-14.7 (12.0)	12.8-14.7 (13.8)	12.0-16.0 (14.0)	14.0-16.6 (15.3)	12.1-17.0 (14.5)	13.7-19.9 (16.8)

Note: PIT and SPUN indicate pit cast and spun cast respectively. H, V, I, D, S and Y denote horizontal, vertical, imported, DeLavaud, Super DeLavaud and Yennora casting methods respectively.

- **Soil modulus $\boldsymbol{E_s}$**: an elastic soil parameter used in the settlement, compression or movement of soils. It is the slope of stress–strain curve in the elastic deformation region for the soil. Units are in MPa. $\boldsymbol{0 < E_s}$.
- **Lateral earth pressure coefficient:** the lateral earth pressure coefficient at rest and can be calculated by:

$$k = 1 - \sin \emptyset \tag{1}$$

where $\emptyset$ is the soil friction angle. $\mathbf{0 \leq k}$.

- **Soil unit weight $\boldsymbol{\gamma_s}$:** the ratio of the total weight of soil to the total volume of soil. Soil unit weight or bulk unit weight is the unit weight of soil and varies for different soil types. Units are in kN/m^3. The values are typically between 15 kN/m^3 to 20 kN/m^3. $\mathbf{0 < \gamma_s}$.

It should be noted that the Time to Failure module is limited to be valid within the range of variables for buried pipes, as listed in Table 2, where the units for each input variable are given. It can be applied for variables outside these limits, albeit the results have to be checked. Thermal stress due to temperature changes is not considered in the Time to Failure module.

Table 2. Physical properties for large-diameter cast iron buried pipes

Description of physical parameters		Symbol	Unit	Value for NLR*
Location	Burial depth	h	mm	300, 800, 1300, 2000
Backfill soil surrounding pipelines	Soil modulus	E_s	MPa	2, 4, 10, 25, 50
	Unit weight	γ	kN/m^3	18.5
	Lateral earth pressure coefficient	k		0.1, 0.25, 0.4
	Poisson's ratio	v_s		0.3
Pipe physical properties (cast iron)	Elastic modulus	E_p	GPa	100
	Poisson's ratio	v_p		0.3
	Wall thickness	T	mm	4, 8, 10, 15, 27
	Internal diameter	D	mm	300, 660, 1000
Load	Traffic load	W	kN	0 to 75
	Maximum allowable pressure	P_{max}	kPa	0, 300, 500, 800, 1000, 1300, 1500

* Values used in conducting the non-linear regression analysis.

In addition to the parameters shown in Figure 2, the pipe stress analysis also requires the input of the dimensions of the semi-ellipsoidal defects. The users have two options to input the dimensions of the corrosion patches.

Option 1: Manual input of patches by users (Single- or multiple-patch input)

As shown in Figure 6, the geometry of the corrosion patch (patch length $2a$, patch width $2b$ and patch depth c) can be manually inputted. The geometry and dimensions of a semi-elliptical corrosion patch is shown in Figure 7.

Patch length (2*a*): corrosion defects are approximated as semi-ellipsoids (Figure 7). Patch length is the length of the corrosion patch along the pipe longitudinal axis.

Patch width (2*b*): the width (*2b*) of the corrosion patch along the pipe circumference (Figure 7). Note that half of the patch width *b* should be no larger than half of the patch length *a* and 250 mm.

Patch depth (*c*): the depth of the corrosion patch along the pipe radial direction (Figure 7). Note that the patch depth *c* should be smaller than the pipe wall thickness allowing for uniform corrosion *T*.

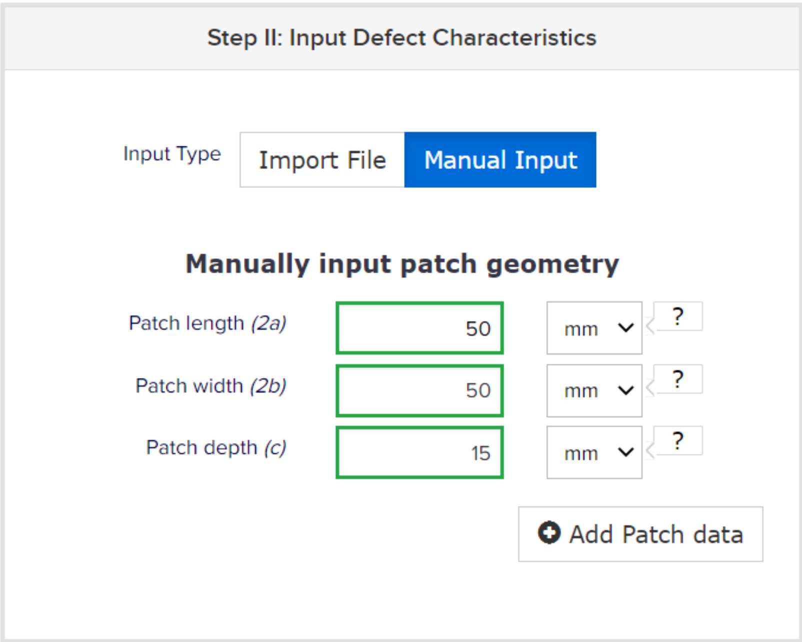


Figure 6. Input of the dimensions of a corrosion patch

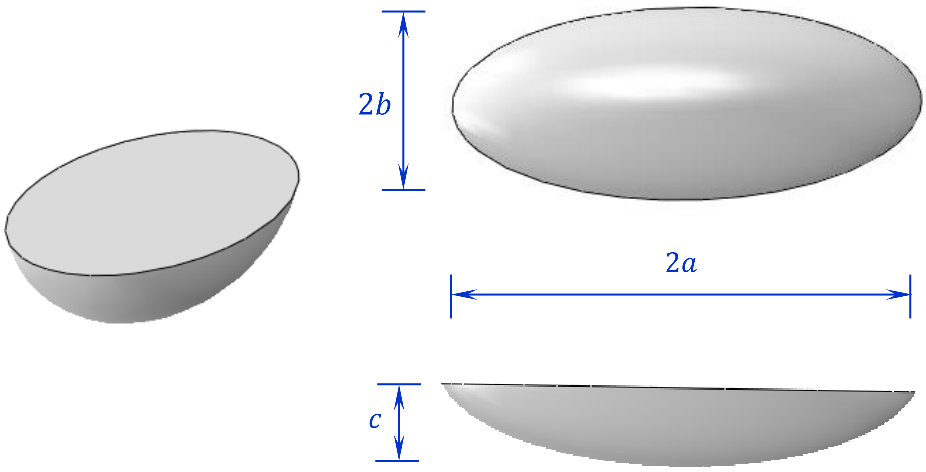


Figure 7. Geometry and dimensions of a semi-ellipsoidal corrosion patch

Note that patch length $2a$ should align with the pipe axis. The dimension c is the depth of corrosion at the middle of the patch (see Figure 5), which should be less than the pipe wall thickness allowing for uniform corrosion.

Multiple corrosion patches can be manually inputted by changing the patch length $2a$, patch width $2b$ and patch depth c and clicking on "Add patch data".

Option 2: Scanned thickness map

A second way of inputting corrosion patches is to use the scanned thickness maps of corroded cast iron pipe segments. A CSV file of the scanned thickness maps can be imported into the platform (Figure 8). The data format of the CSV file is shown in Figure 9 (a). The first row the inputting CSV file contains the coordinates along the pipe length ($0 - L$) with a certain interval depending on the scanning resolution while the first column stores the coordinates along the pipe circumference with a certain interval. The remaining cells in the CSV file (e.g., within the green box shown in Figure 9 (a)) are the data on the scanned pipe wall thickness, evaluated in terms of wall loss in percentage (%) (penetration depth $P \times 100$/pipe wall thickness T). Note that the first cell should have a value of "0". Based on a patch identification algorithm, corrosion patches in the scanned thickness maps can be identified (Figure 9 (b)) and outputted for pipe stress analysis.

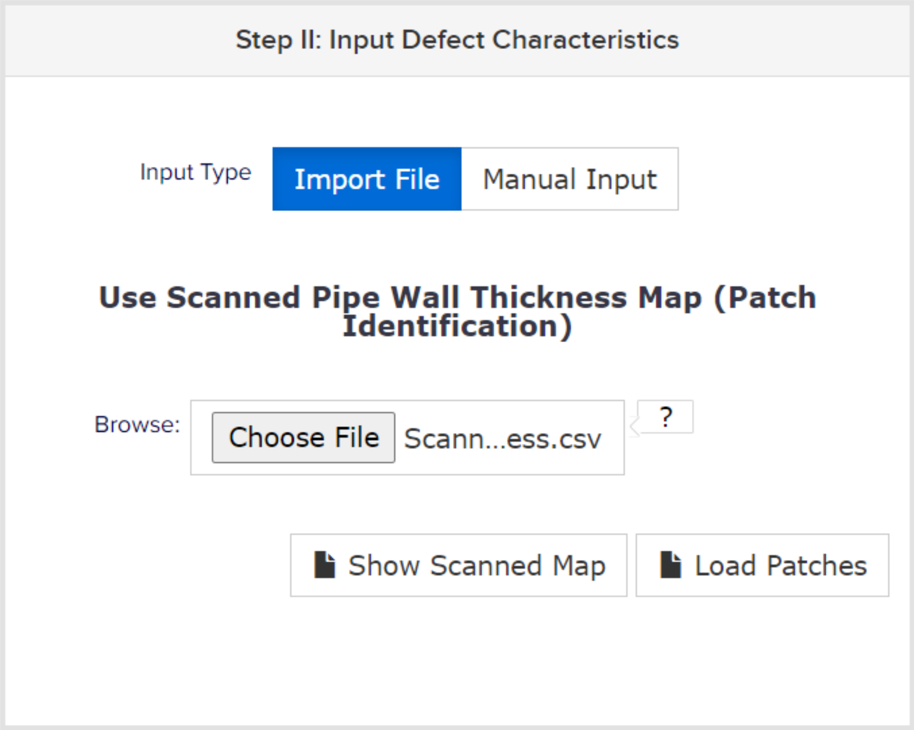
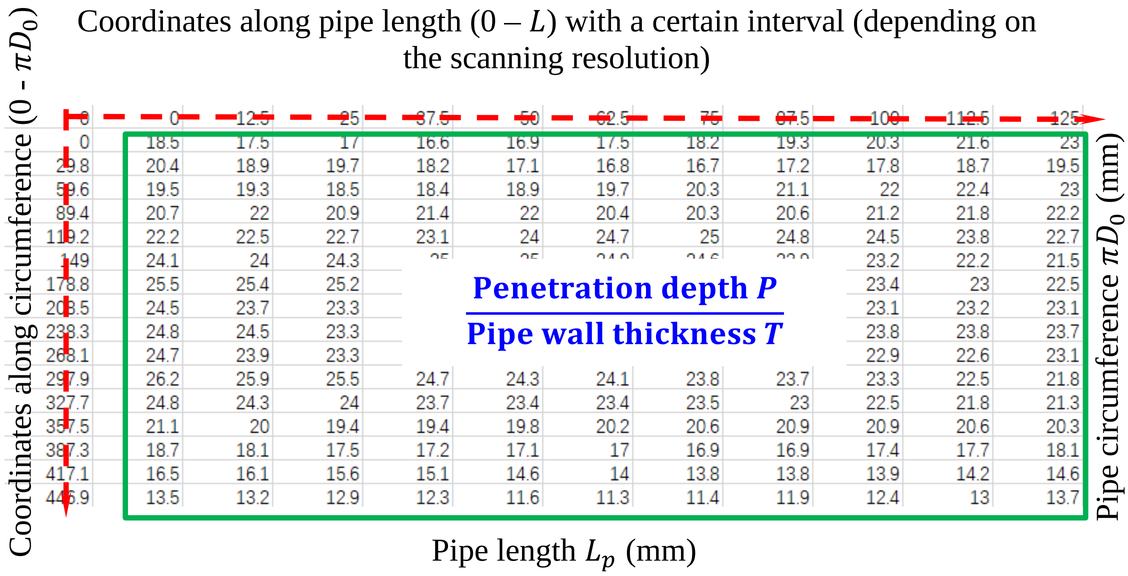
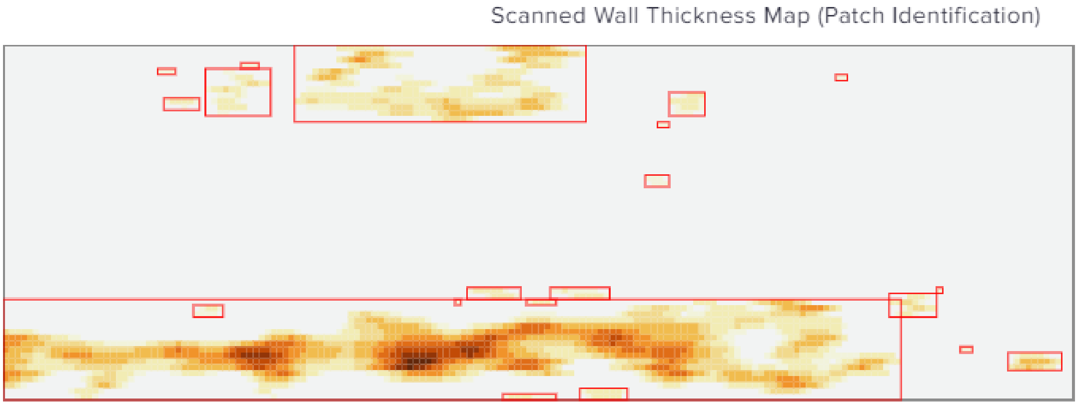


Figure 8. Importing scanned thickness maps



(a) Data format of the CSV input file



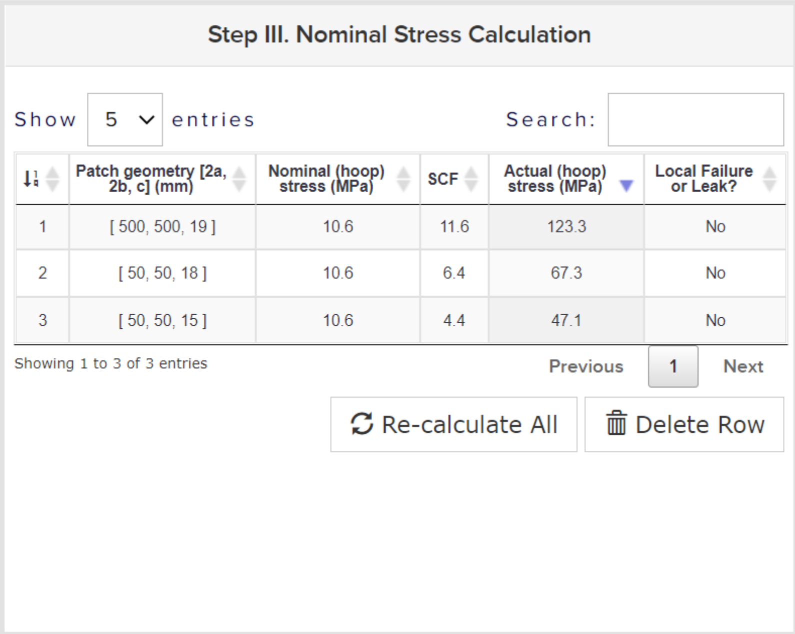
(b) identified corrosion patches in the scanned thickness map

Figure 9. (a) Example data used for scanned thickness map (b) Example of a scanned thickness map

1.1.2 Output

Based on the above -mentioned input variables, the nominal (hoop) stress (Robert et al. 2016), stress concentration factor (SCF) (Fu et al. 2020) and actual (hoop) stress can be calculated for each corrosion patch as shown in Figure 10. When the scanned thickness map is used for defect characteristics, one output from the patch identification algorithm is the estimated uniform corrosion loss. This estimation is used to update the value of "*T*" in the pipe properties section. After stress calculation, these identified corrosion patches will be ranked by their calculated actual (hoop) stresses.

If the calculated actual (hoop) tensile stress $\boldsymbol{\sigma_{max}}$ is no smaller than the ultimate tensile strength $\boldsymbol{\sigma_t}$, a local failure or initiation of a leak will occur. Otherwise, no local failure or initiation of a leak will occur.



Step III. Nominal Stress Calculation

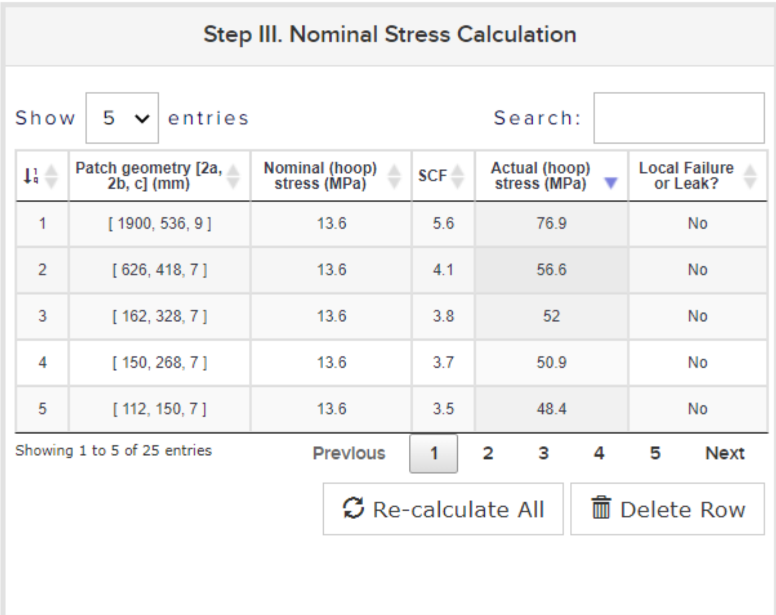
Show 5 entries Search:

↓	Patch geometry [2a, 2b, c] (mm)	Nominal (hoop) stress (MPa)	SCF	Actual (hoop) stress (MPa)	Local Failure or Leak?
1	[500, 500, 19]	10.6	11.6	123.3	No
2	[50, 50, 18]	10.6	6.4	67.3	No
3	[50, 50, 15]	10.6	4.4	47.1	No

Showing 1 to 3 of 3 entries Previous 1 Next

Re-calculate All Delete Row

(a) Manual input of multiple patches



Step III. Nominal Stress Calculation

Show 5 entries Search:

↓	Patch geometry [2a, 2b, c] (mm)	Nominal (hoop) stress (MPa)	SCF	Actual (hoop) stress (MPa)	Local Failure or Leak?
1	[1900, 536, 9]	13.6	5.6	76.9	No
2	[626, 418, 7]	13.6	4.1	56.6	No
3	[162, 328, 7]	13.6	3.8	52	No
4	[150, 268, 7]	13.6	3.7	50.9	No
5	[112, 150, 7]	13.6	3.5	48.4	No

Showing 1 to 5 of 25 entries Previous 1 2 3 4 5 Next

Re-calculate All Delete Row

(b) Automatic identified corrosion patches from the scanned thickness map (Figure 9)

Figure 10. Pipe stress analysis results (a) manual input of multiple patches and (b) automatic identified corrosion patches

1.1.3 Notes

- The calculated SCF considers the influence of a 2nd small corrosion defect that is hardly detectable at the bottom of a primary corrosion patch/pit. Our numerical findings demonstrate that 1) the 2nd defect can cause a significant higher value of the SCF; 2) simply increasing the depth of the primary corrosion patch/pit to account for the depth of 2nd defect is found to result in an underestimate of the actual impact of the 2nd pit. For practical purposes, a factor of 1.5 of the SCF based on a series of preliminary numerical investigation is incorporated in the calculation of the SCF. However, the influence is dependent on the size and depth of the 2nd defect.
- Please note that an in-situ irregular corrosion defect needs to be idealised into an equivalent ellipsoid (or crater) shape, and the corrosion depth *c* is the maximum corroded depth within the corrosion defect,

as shown in Figure 11. This methodology is similar to the procedure given in ASME B31G (2012), but has been checked by Monash researchers for applicability to water pipes.

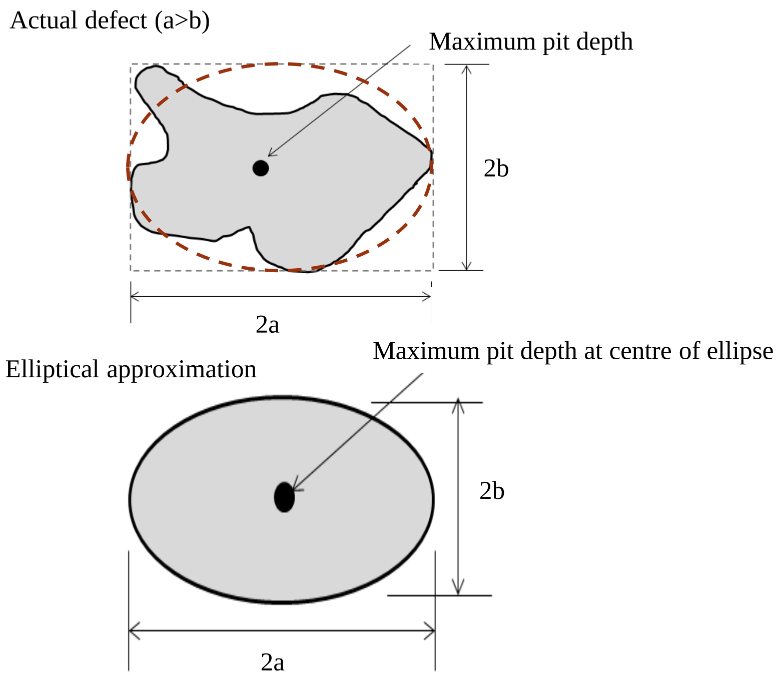


Figure 11. Approximation of irregular corrosion geometry by an ellipsoid

- For an oriented corrosion defect, the length 2*a* varies as per the changes of the orientation angle, θ, as indicated in Figure 12. This methodology was adopted from ASME B31G (2012), and has been checked by Monash researchers for applicability. Note that the current patch identification algorithm used for scanned thickness maps was developed based on the bounding boxes of the corrosion defects and it does not calculate the orientation angle θ.

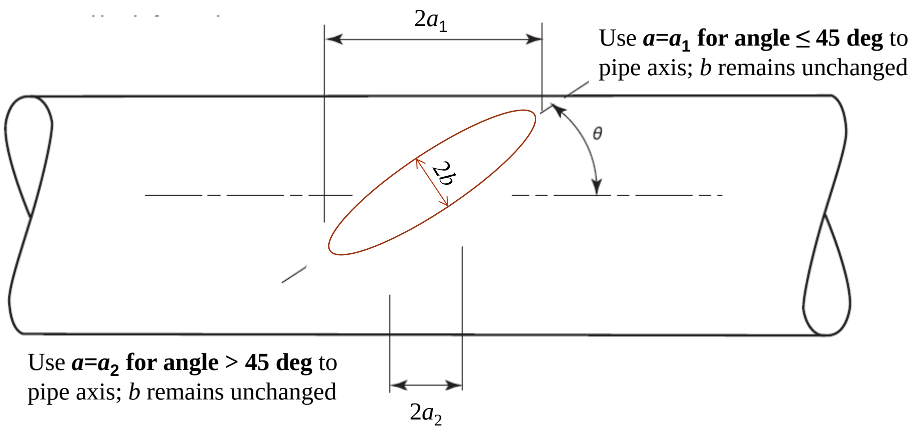


Figure 12. Change of length, 2a, for an oriented corrosion defect

It is expected that fracture initiation may lead to a “LEAK”. However, in reality, whether a leak will occur or not would depend on the length of the crack generated through initial failure. For small pits, pit basal failures will mean the creation of through-wall holes and some of these through-wall holes may not leak due to cement lining bridging it and/or graphitisation plugging the pit. For larger patches, however, a larger crack may be generated, which can lead to leakage.

1.2 Remaining Life Prediction/Time to Failure

1.2.1 Time to Failure due to Corrosion

In the pipe stress analysis, no local failure or leak for a potential critical corrosion patch means that the corrosion patch has not progressed to a sufficient size to form a leak. Therefore, this corrosion patch can be selected to further evaluate the remaining life before a leak/burst provided that the radial and lateral corrosion extension rates are known. It should be noted that the remaining life depends on how the corrosion patch grows over time. Please also note that due to lack of data on corrosion patch development, isotropic corrosion growth, in which the patch grows at the same rate in the longitudinal and circumferential directions, is assumed in the current Time to Failure module. Once more data is available, this assumption can be relaxed and different values can be then assigned for corrosion growth in the longitudinal and circumferential directions.

1.2.2 Input pipe parameters (Time to failure)

In addition to the input parameters summarized in Figure 2 and the dimensions (2*a*, 2*b*, *c*) of the selected corrosion patch (Figure 10 (a)), the radial and lateral extension rates are needed for the patch to grow over time.

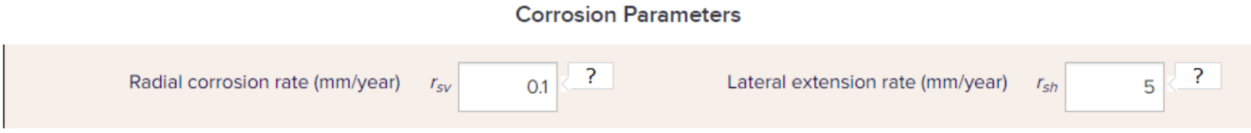


Figure 13. Inputting corrosion parameters

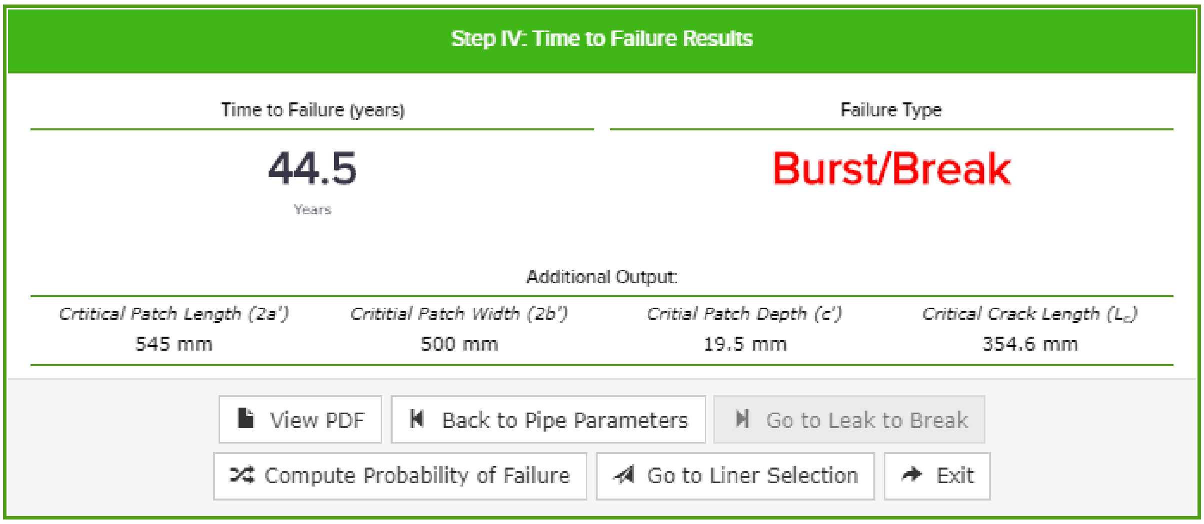
- **Radial corrosion rate r_{sv}**: the increment of the corrosion patch depth per year. Corrosion patch depth (c_t) after *t* years $c_t = c_0 + r_{sv} \times t$, where c_0 is the current patch depth. Units are in mm/y. $\mathbf{0 \leq r_{sv}}$.
- **Lateral extension rate r_{sh}**: the increment of corrosion patch length and width per year. Half of the corrosion patch length (a_t) and half of the corrosion patch width (b_t) after t years can be calculated by $a_t = a_0 + r_{sh} \times t$, $b_t = b_0 + r_{sh} \times t$ respectively, where a_0 and b_0 are the current half of the patch length and half of the patch width respectively. Units are in mm/y. $\mathbf{0 \leq r_{sh}}$.

1.2.3 Output (Time to failure)

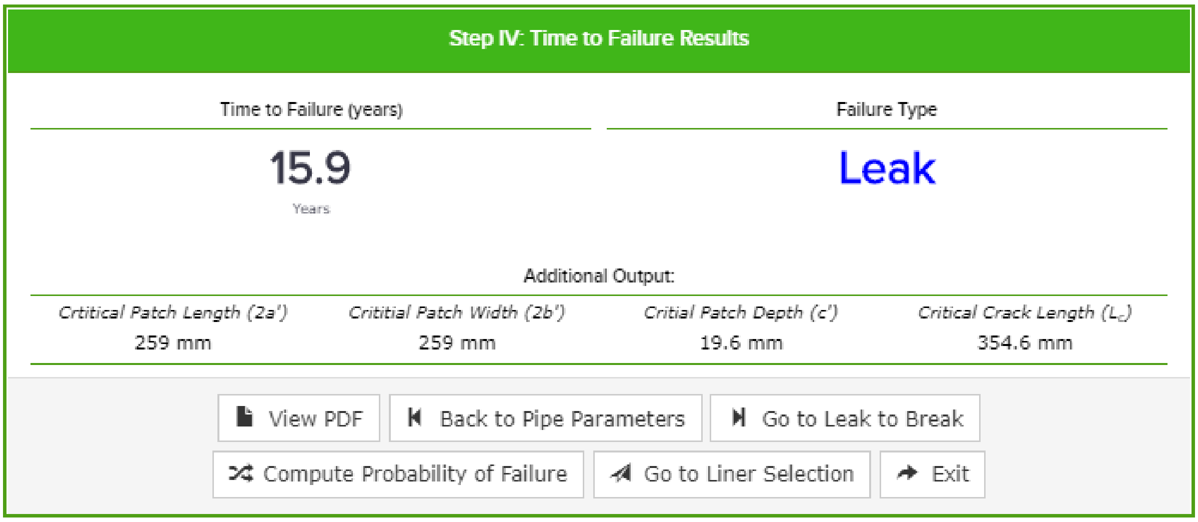
Click the “Compute Time to Failure” button to calculate the estimated remaining life of the pipe. Herein, the time to failure is based on deterministic inputs, with no consideration of any kinds of uncertainty. Note that a “0” year Time to Failure implies that the pipe has already/should have leaked or broken. The Time to Failure results are shown in Figure 14. Apart from the time to failure, the critical patch length $2a'$, the critical patch width $2b'$, the critical patch depth c' and the critical crack length L_C are determined. It is known that once a fracture is formed through basal failure of a patch (and possibly a LEAK), the pipe failure type may be “Leak” or “Burst/Break”. The failure type is determined here by comparing the critical patch length $2a'$ and the critical crack length L_C. If the $2a'$ is greater than the L_C, the pipe failure type is considered to be “Burst/Break”. Otherwise, the pipe failure type is considered to be “Leak”. Please note that this calculation is approximate at this stage since it does not use the actual crack length generated in the initial failure, but the length of the corrosion patch (i.e., $2a$) as the referenced crack length. Therefore, the calculation provides a conservative assessment. It is considered that the burst will occur, when the stress intensity factor (SIF) equals the fracture toughness of the pipe material.

For the corrosion patch with dimensions (2*a* = 100 mm, 2*b* = 100 mm, *c* = 15 mm), the time to failure is 44.5 years as shown in Figure 14 (a) and the failure type is “Burst/Break” as the critical patch length $2a'$ is larger than the critical crack length L_C.

For the corrosion patch with dimensions (2*a* = 100 mm, 2*b* = 100 mm, *c* = 18 mm), the time to failure is 15.9 years as shown in Figure 14 (b) and the failure type is “Leak” as the critical patch length $2a'$ is smaller than the critical crack length L_C.



(a) Corrosion patch with dimensions ($2a$ = 100 mm, $2b$ = 100 mm, c = 15 mm)



(b) Corrosion patch with dimensions ($2a$ = 100 mm, $2b$ = 100 mm, c = 18 mm)

Figure 14. Time to Failure results

In the Time to Failure analysis, if the failure type is “Leak”. The user may proceed to conduct Leak to Break analysis by clicking on the “Go to Leak to Break” button.

1.2.4 Leak to Break due to Pressure Transient

The Leak to Break Model assesses the potential burst failure of corroded cast iron pipes caused by pressure transients once a leak occurs and it will determine the time window for leak before break. It should be noted that the current Leak to Break Model is just a preliminary tool, developed based on the findings of the ACAPFP project. There are a number of assumptions that were made (e.g., the initial crack length at breakthrough is assumed to be 5 mm) and this tool has not been validated yet.

When the pipe maximum stress exceeds the tensile strength of the cast iron, a crack will initiate at the bottom of the corrosion patch. Due to pressure transient caused sub-critical crack propagation, the crack grows with time up to a critical length when the pipe will burst/break. The time period from crack initiation to the critical length is defined as the time window for leak before break.

1.2.5 Input pipe parameters (Leak to Break)

Based on the Time to Failure due to Corrosion, additional parameters are required for the Leak to Break analysis (Figure 15).

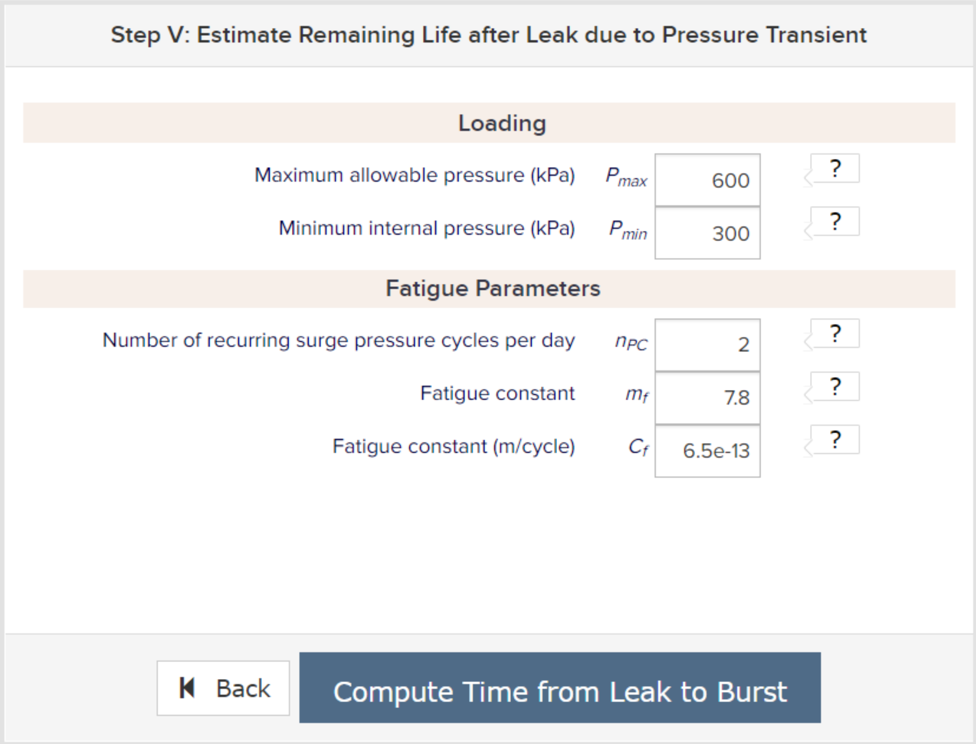


Figure 15. Input parameters for Leak to Break model

- **Maximum allowable pressure $\boldsymbol{P_{max}}$:** the maximum pressure applied to the pipe, which equals to the sum of the operating pressure and the surge pressure. Units are in MPa. $\mathbf{0} \leq \boldsymbol{P_{max}}$
- **Minimum internal pressure $\boldsymbol{P_{min}}$:** the minimum pressure applied the pipe due to recurring surge pressures. Units are in MPa. $\mathbf{0} \leq \boldsymbol{P_{min}}$.
- **Number of cycles per day $\boldsymbol{n_{PC}}$:** the number of cyclic surge pressure cycles per day. n_{PC} should be obtained from pressure transient monitoring of the pipe segment. $\mathbf{0} \leq \boldsymbol{n_{PC}} \leq \mathbf{1000\ cycles/day.}$
- Maximum pressure, minimum pressure and number of cycles per day: these three parameters should be obtained from pressure transient monitoring of the pipe segment.
- **Fatigue constant $\boldsymbol{m_f}$:** a fatigue constant in Paris' law. This fatigue constant is unitless. $\mathbf{0} < \boldsymbol{m_f}$.
- **Fatigue constant $\boldsymbol{C_f}$:** a fatigue constant in Paris' law. Units are in m/cycle. $\mathbf{0} < \boldsymbol{C_f} < 10^{-5}\ \mathbf{m/cycle.}$
- Fatigue constants $\boldsymbol{m_f}$ and $\boldsymbol{C_f}$: fatigue testing (ASTM E647 2005) on either single-edge notched beam (SENB) or compact tension (CT) specimens should be conducted to determine these two constants. If no testing is conduced, then Table 3 may be used.

Table 3. *Fatigue constants from literature (Rathnayaka et al. 2017)*

Specimen	R	m_f	C_f (m/cycle)	Reference
SENB	0.1	7.4-8.0	2.1×10^{-16} – 4.6×10^{-15}	Mohebbi et al. (2010)
SENB	0.1	9.4-11.3	9.6×10^{-21} - 1.3×10^{-15}	Rajani et al. (2012)
SENB	0.1, 0.5	7.0-7.5	1.0×10^{-14} – 5.0×10^{-15}	Baicchi et al. (2007)
CT	0.05, 0.3, 0.7	6.2-6.7	6.1×10^{-16} - 2.6×10^{-12}	Bulloch (1995)
CT	0.01	5.9-7.2	6.0×10^{-15} - 2.0×10^{-16}	Hornbogen (1985)
CT	0.1	5.5	1.8×10^{-14} - 5.1×10^{-15}	Kapadia and Imhof (1979)
SENB	0.1, 0.3, 0.5	4.5-11.9	1.4×10^{-17} – 8.0×10^{-12}	Rathnayaka et al. (2017)

1.2.6 Output (Leak to Break)

Based on the above-mentioned input variables, the estimated remaining life after leak to break due to pressure transients can be calculated (Figure 16).

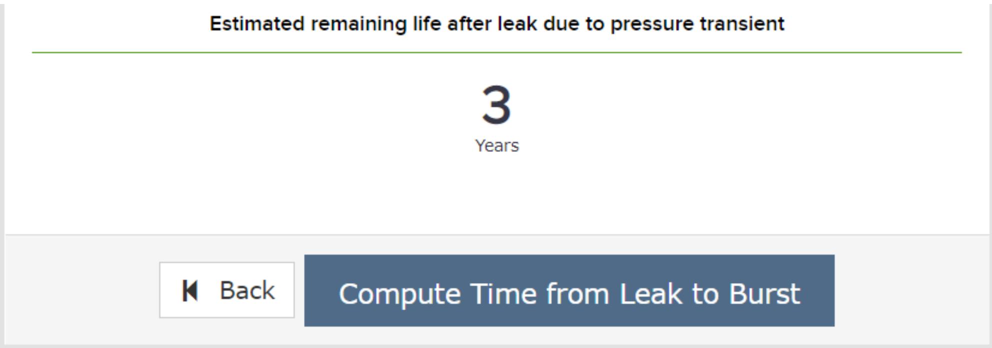


Figure 16. Leak to Break model result

The technical details of the calculation of the remaining life after leak due to pressure transients are provided in Rathnayaka et al. (2017).

1.3 Pipe Failure Probability

The Time to Failure Module has been further developed to incorporate the effect of the uncertainty of key physical parameters (Ji et al. 2017). By modelling the corrosion degradation of the pipes, the prediction in terms of hazard rate and decay curves can be visualized in the Time to Failure Module. For pipelines under assessment, the Time to Failure module allows the users to produce their own prediction curves for probabilistic prediction and long-term planning and management of the pipelines or pipe cohorts. The probabilistic prediction curves for pipeline failure prediction are developed based on the information of key physical parameters and mechanism of pipe failure.

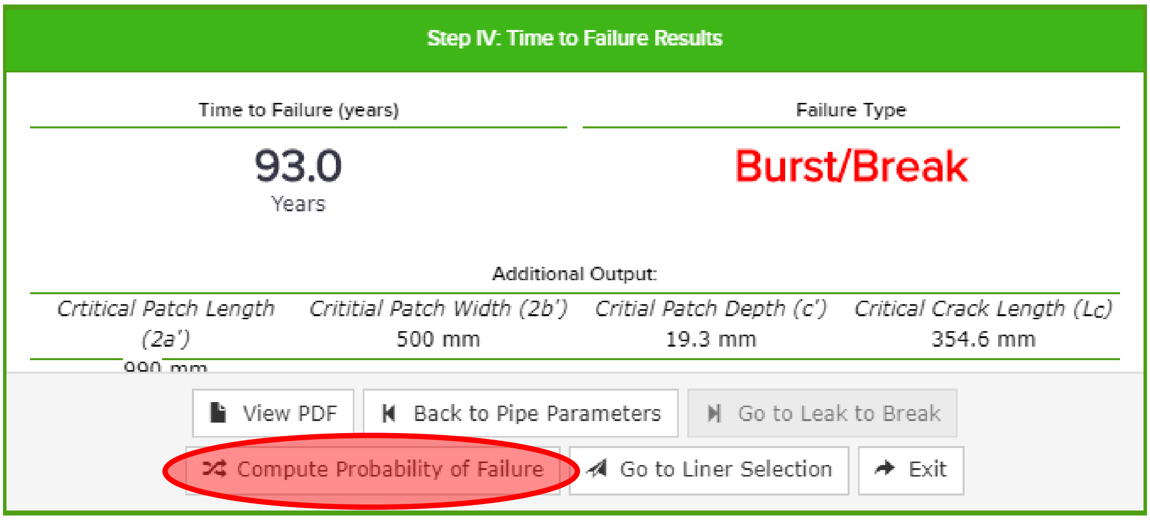
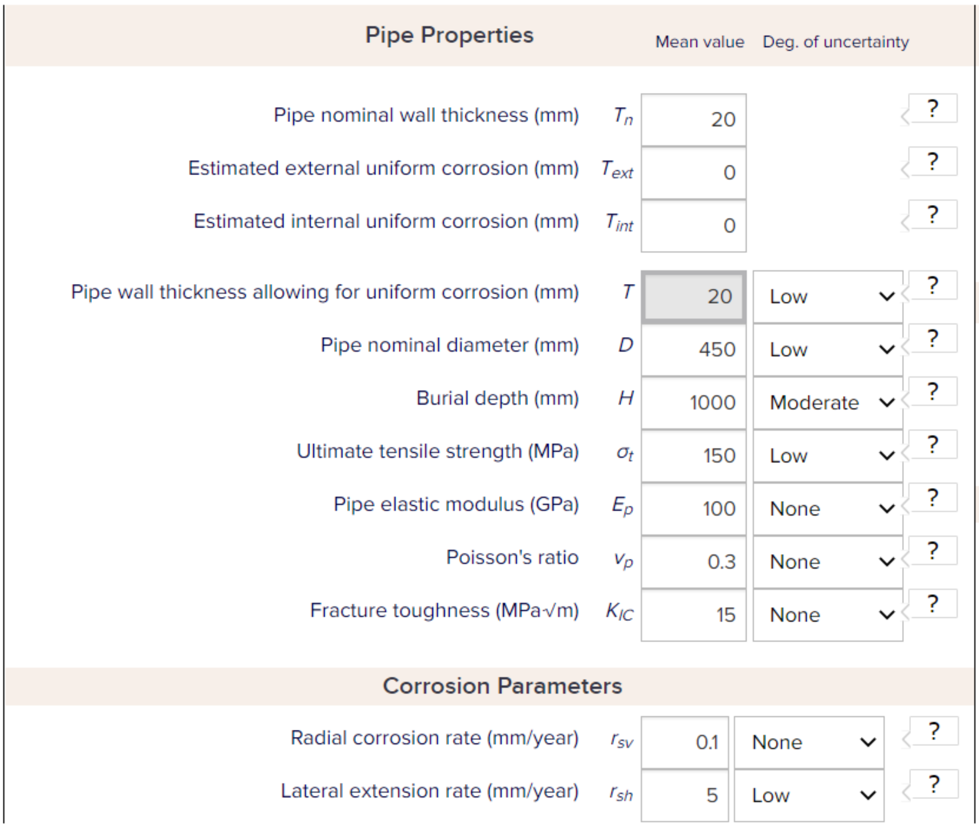


Figure 17. Selection of "Compute Probability of Failure"

After determining the time to failure, the users can click on the button "Computer Probability of Failure" in the result window as shown in Figure 17 to proceed to the pipe failure probability calculation.

1.3.1 Input variables

The inputs shown in Sections 1.1 and 1.2 are needed, together with the specified degree of uncertainty for each parameter. Users are required to select a certain level of uncertainty for the parameters shown in Figure 18. These inputs, including numerical values and degree of uncertainties, provide information of pipe physical parameters.



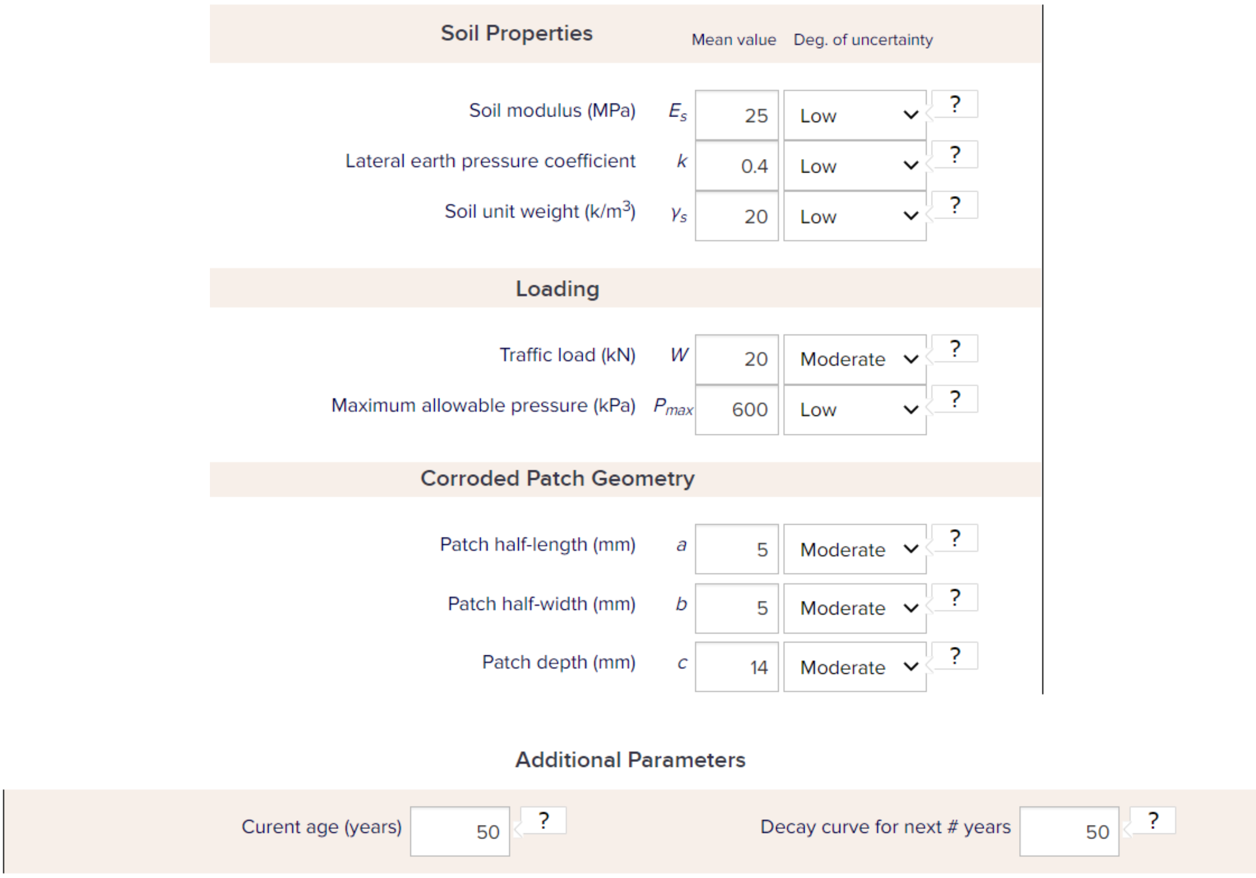


Figure 18. Input parameters for pipe failure probability

- **Current Age # Years**: the period of time from pipe installation to current time (years). The input value should be non-negative.
- **Decay Curve for Next # Years**: the period of time the Decay Curves (Probability of Curves) will be predicted for (years). The input value should be non-negative.
- **Mean value**: is the average of each of the parameters used in analysis. For example, 100 (GPa) is used for the pipe elastic modulus E_p.
- **Degree of uncertainty**: specifies the standard deviation. There are three levels as defined in Monash Tool:
    - None: uncertainty is not considered
    - Low: standard deviation = 0.1×mean value
    - Moderate: standard deviation = 0.25×mean value
    - High: standard deviation = 0.5×mean value

  Note: For a fast set-up of the input uncertainties, a default option is provided by clicking the button Default DoU. Users may choose whichever level the parameter is at based on their own judgement. The additional input is the current age of the pipe.

1.3.2 Output

By clicking on the button "**Computer Probability of Failure (Hazard rate & Decay Curves)**", the results of physical probabilistic analysis are shown in Figure 19.

The hazard rate is given as a percentage number, indicating the probability of pipe failure for the next specified year. For example, the probability of failure (hazard rate) is 3.60% for one of the case studies being analysed.

This result provides a view of the pipe's instantaneous failure risk at the current lifetime, e.g., the current state of condition assessment.

The obtained decay curves are also shown in Figure 19. There are three curves produced: instantaneous probability of failure (hazard rate), cumulative probability of failure, and mean remaining lifetime (secondary vertical axis).

- For example, the decay curves in Figure 19 demonstrate that the pipe at its current age, 50 years, is subjected to 3.60% probability of failure, and the cohort of these pipes has a 41% cumulative failure probability, the remaining lifetime of the pipe is expected to be 12 years.
- Because the Time to Failure model is designed to predict the remaining lifetime behaviour of a pipe, no decay curve is presented before the current state.

Figure 19. Results for pipe failure probability

2 LIFETIME PROBABILITY OF FAILURE

The Lifetime Probability of Failure module is used to conduct lifetime probability of failure analysis. It is capable of producing the probabilistic prediction curves (decay curves) based on the mechanism of pipe failure and the statistical information of key physical parameters. Due to lack of information of corrosion initiation time, adjustments to the probabilistic prediction curves can be made if past failures are available so that the prediction curves can be used at a higher confidence level. For a pipeline that consists of a number of pipe spools, the number of failures in the next several years can be predicted using the probabilistic prediction curves.

2.1 Input variables

The inputs include pipe properties, soil properties, loading, corrosion model and failure history, together with the specified degree of uncertainty for some key parameters. Users are required to give inputs for the parameters shown in Figure 20. The inputs for the parameters with uncertainty include expected values and coefficients of variations. Note that the coefficient of variation (CoV) is defined as the ratio of the standard deviation to the mean/expected value.

Pipe Properties		Mean value	CoV	
Pipe age (years)		53		?
Pipe wall thickness (mm)	T	17	0.1	?
Pipe nominal diameter (mm)	D	500	0.1	?
Pipe length (m)	L_p	476		?
Pipe spool length (m)	L_{ps}	3.66		?
Burial depth (mm)	H	1000	0.1	?
Ultimate tensile strength (MPa)	σ_t	150	0.1	?
Pipe elastic modulus (GPa)	E_p	100	0.0001	?
Poisson's ratio	v_p	0.3	0.0001	?
Failure History				
Time period (years) for the recorded number of failures		10		?
Number of past failures	n_p	2		?

Soil Properties		Mean value	CoV
Soil modulus (MPa)	E_s	25	0.01
Lateral earth pressure coefficient	k	0.4	0.01
Soil unit weight (k/m^3)	γ_s	20	0.01
Loading			
Traffic load (kN)	W	50	0.01
Maximum allowable pressure (kPa)	P_{max}	500	0.3
Corrosion Model			
Long-term, steady state corrosion rate	r_s	0.04814	0.25
Intercept parameter for long-term corrrosion (mm)	c_s	5.03335	0.25
Transition between short- and long-term corrosion (years)	τ	25	0.25
Aspect ratio	k_2	10	0.3
Patch factor	k_1	2	0.3

Figure 20. Input parameter for lifetime probability of failure analysis

Apart from the parameters shown in Figure 18 and explained in Section 1.3, there are some other parameters used in the lifetime probabilistic analysis.

- **Pipe age:** the period of time from pipe installation to the current time for condition assessment (years). It can be calculated based on the pipe installation year. Pipe age should be non-negative.
- **Pipe length L:** the length of the pipeline section under investigation. The pipe length should be positive.
- **Pipe spool length L_s:** the length of each pipe spool for the pipeline under investigation. Pipe spool length should be positive.
- **Failure history:** the number of past failures and the time period for the recorded number of failures are required to calibrate the calculated probability of failure curved in order to determine the honeymoon period, as there is lack of information on the corrosion initiation time.
- **Time period for the recorded number of failures:** the period of time during which the number of past failures were recorded. The time period for the recorded number of failures should be non-negative.
- **Number of past failures n_p:** the number of failures which has been recorded in the past. The number of past failures should be non-negative.
- **Corrosion model:** the exponential corrosion model (Figure 21) is used for lifetime probability of failure analysis:

$$P = r_s t + c_s\left(1 - exp^{-\frac{t}{\tau}}\right) \tag{2}$$

- **Long-term corrosion rate r_s:** the long-term steady state corrosion rate of metallic pipes (mm/year) in the exponential corrosion model.

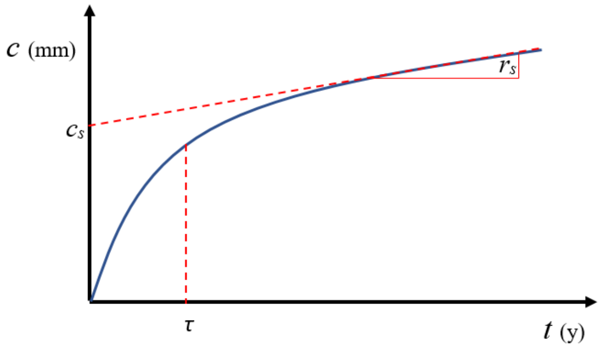
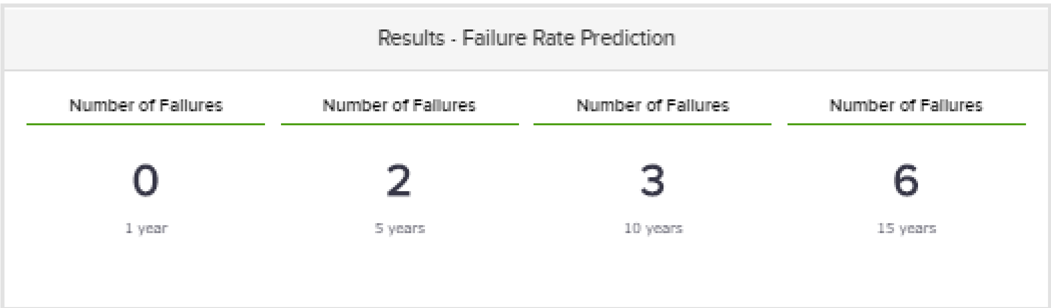


Figure 21. Exponential corrosion model

- **Intercept parameter for long-term corrosion c_s:** the intercept parameter between initial and long-term corrosion rate of metallic pipes (mm) in the power law corrosion model
- **Transition time:** the time it takes for the pit depth to attain around 63% of the maximum value in the absence of long-term corrosion rates (i.e., r_s = 0). If no value is available, then a value of 15 years is suggested to be used according to a careful review of the existing data in literature.
- **Aspect ratio:** the value is calculated by dividing half of the corrosion patch length (a) by patch depth (c). This ratio determines how the corrosion patch grows in the longitudinal and radial directions. A proper value can be selected based on the inspection of the corrosion patches identified from the scanned thickness maps of the excavated pipe segments.
- **Patch factor:** the value is calculated by dividing the corrosion patch length ($2a$) by patch width ($2b$). This ratio determines how the corrosion patch grows in the longitudinal and circumferential directions. A proper value can be selected based on the inspection of the corrosion patches identified from the scanned thickness maps of the excavated pipe segments.
- For other pipe properties, soil properties and loadings, please refer to Section 1.1 for details.

2.2 Output

Click the “Lifetime probability of failure analysis” button to conduct the lifetime probability of failure analysis.



The probabilistic results contain the predicted number of failures for the next 1 year, 5 years, 10 years, and 15 years for the analysed pipeline section.

NOTATION

$2a$	Patch length (mm)
$2a'$	Critical patch length (mm)
$2b$	Patch width (mm)
$2b'$	Critical patch width (mm)
c	Patch depth (mm)
c'	Critical patch depth (mm)
c_s	Intercept parameter for long-term corrosion of metallic pipes (mm)
C_f	Fatigue constant for host pipe under cyclic surge pressure
d	Initial hole (defect) size (mm)
D	Pipe internal diameter (mm)
D_0	Pipe external diameter (mm)
D_M	Mean diameter of the host pipe (mm)
DN	Pipe nominal diameter (mm)
E_p	Modulus of elasticity of host pipe material (GPa)
E_s	Soil modulus (MPa)
g	Acceleration due to gravity (m/s^2)
h	Pressure head (m)
H	Burial depth (mm)
H_w	Groundwater depth (mm)
k	Lateral earth pressure coefficient
k_1	Patch factor
k_2	Aspect ratio
K	Enhancement factor
K_{IC}	Fracture toughness of host pipe material (MPa m$^{1/2}$)
L_c	Critical crack length (mm)
L_p	Length of the pipe (m)
L_{ps}	Length of the pipe spool (m)
m_f	Fatigue constant for host pipe under cyclic surge pressure
$MAOP$	Maximum allowable operational pressure (MPa)
n_f	Cyclic surge factor
n_{PC}	Number of recurring cyclic surge pressure cycles per day
n_{TPC}	Total number of surge pressure cycles for the service life of pipe/lined pipe
N	Safety factor for host pipe
P	Operating pressure (MPa)
P_G	Groundwater load (MPa)
P_{GC}	Groundwater load capacity (MPa)
PN	Nominal pressure (bar)

P_N	External pressure on the liner (MPa)
P_T	Test pressure (MPa)
P_c	Recurring cyclic surge pressure (MPa)
P_{max}	Maximum allowable pressure (MPa)
P_{min}	Minimum internal pressure (MPa)
P_s	Surge pressure (MPa)
P_v	Vacuum pressure (MPa)
q_t	Total external pressure on pipes (MPa)
q_{tc}	Liner capacity for total external pressure (MPa)
r_s	Minimum corrosion rate (long-term) of metallic pipes (mm/y)
r_{sh}	Lateral extension rate for metallic pipes (mm/y)
r_{sv}	Radial corrosion rate for metallic pipes (mm/y)
SCF	Stress concentration factor
SCF'	Critical stress concentration factor
t	Time (years)
T	Pipe wall thickness allowing for uniform corrosion (mm)
T_{ext}	Estimated external uniform corrosion (mm)
T_f	AC pipe remaining wall thickness at failure (mm)
T_{int}	Estimated internal uniform corrosion (mm)
T_L	Liner thickness (mm)
T_n	Pipe nominal wall thickness (mm)
W	Traffic load (kN)
W_s	Live load (MPa)
α	Coefficient of thermal expansion/contraction (mm/mm/°C)
β	Fraction of liner service life when out of service
γ_s	Soil unit weight (kN/m^3)
γ_w	Unit weight of water (kN/m^3)
ΔT	Temperature change (°C)
ν_p	Poisson's ratio of host pipe material
σ_p	Tensile stress in the host pipe (for AC pipe) (MPa)
$\sigma_{t,AC}$	Ultimate tensile strength of AC (MPa)
σ_t	Ultimate tensile strength of host pipe material (MPa)
σ_y	Yield strength of steel (MPa)
τ	Transition period between short-term and long-term corrosion (y)
Φ	Soil friction angle (°)

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DISCLAIMER

1. Use of the information and data contained within the Pipe Failure Analysis module is at your sole risk.

2. If you rely on the information in the Pipe Failure Analysis module, then you are responsible for ensuring by independent verification of its accuracy, currency, or completeness.

3. The information and data in the Pipe Failure Analysis module is subject to change without notice.

4. The Pipe Failure Analysis module developers may revise this disclaimer at any time by updating the Pipe Failure Analysis module.

5. Monash University and the developers accept no liability however arising for any loss resulting from the use of the Pipe Failure Analysis module and any information and data.

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