MONASH PIPE
EVALUATION PLATFORM

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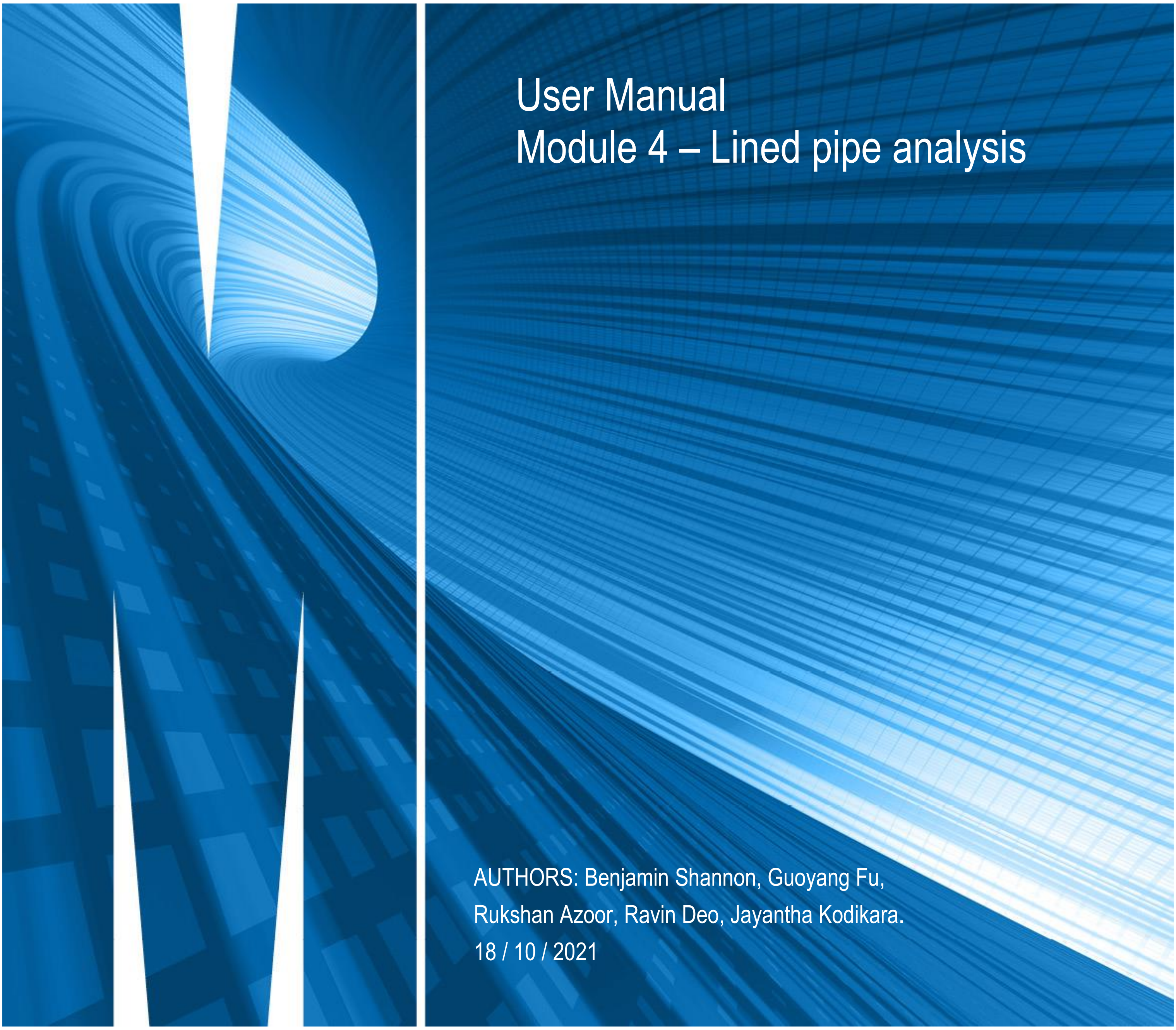

User Manual
Module 4 – Lined pipe analysis

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CONTENTS

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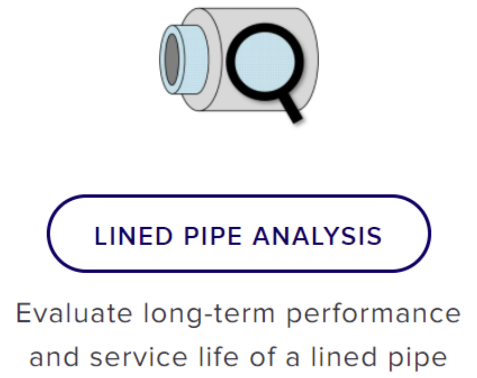
INTRODUCTION

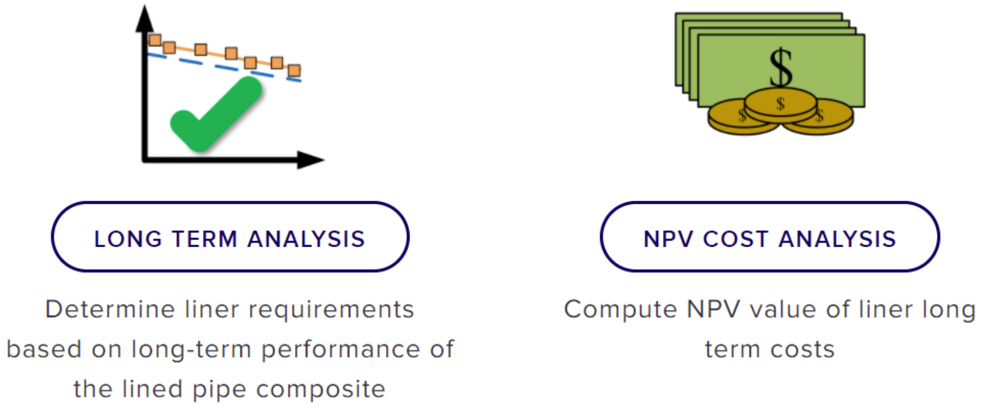
This document outlines the methods and processes used in the lined pipe analysis (Figure 1), and provides guidelines for its use.



Evaluate long-term performance and service life of a lined pipe

Figure 1. Lined pipe analysis module icon in the user interface

The primary function of the lined pipe analysis module is to provide an estimate of the liner service life or thickness and a net present value cost analysis. The long-term analysis approach or NPV cost analysis options are provided at the start of the module (Figure 2).



Determine liner requirements based on long-term performance of the lined pipe composite

Compute NPV value of liner long term costs

Figure 2. Long-term analysis and NPV cost analysis

1 LONG-TERM ANALYSIS

The long-term analysis can be conducted for either a single pipe or multiple pipe analysis[1]. The calculation process is organised into a four-step simple workflow, with basic and advanced properties, to determine either:

- Liner design thickness or
- Estimate service life.

The thickness or service life calculations are based on the formulas developed at Monash University and from standards (ASTM F1216 2016; AWWA 2019).

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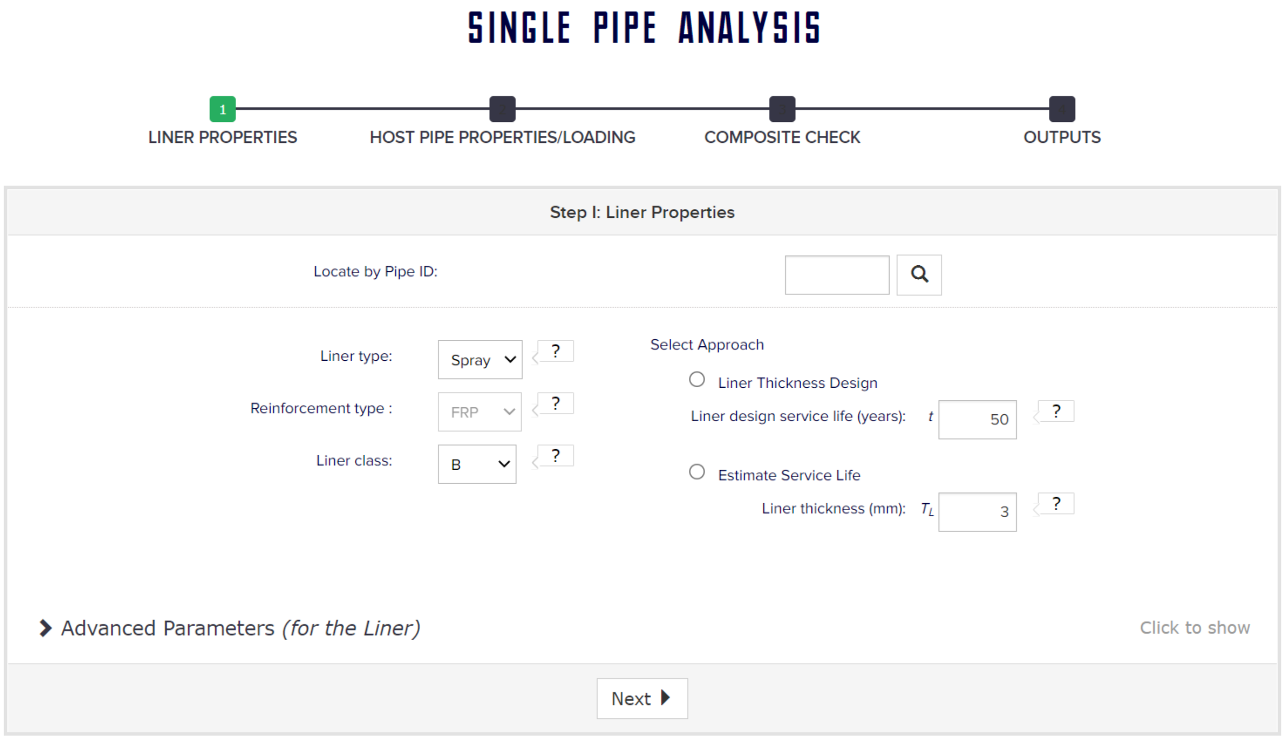
[1] Multiple pipe analysis has not been implemented at this stage.

1.1 Step I-Liner properties

In the liner properties step, the user is required to select the type of liner, either **Spray or CIPP**, the **liner class** (A, B, C, or D), and the **Reinforcement type** (for CIPP only, categorised as either GFRP (Glass fibres) or FRP (Polymeric fibres)). The user interface is given below in Figure 3. Two different approaches can be selected. Liner thickness design will determine the minimum wall thickness required for the lined pipe to survive the inputted liner design service life, whereas Estimate service life uses a liner thickness value to determine the service life of the lined pipe.



SINGLE PIPE ANALYSIS

Step I: Liner Properties

Locate by Pipe ID:

Liner type: Spray

Reinforcement type : FRP

Liner class: B

Select Approach

○ Liner Thickness Design

Liner design service life (years): t 50

○ Estimate Service Life

Liner thickness (mm): T_L 3

Figure 3. User interface for the failure history step in the pipe level analysis of the liner selection module

- **Liner thickness (T_L) -** The liner thickness required for the specified liner service life. Units are in mm. Liner thickness can be noted as just the reinforcing layer thickness (T_r) (for CIPP only) or total liner thickness (T_L), however this must be noted by the applicator to avoid interchanging of terms. $0 \leq T_L \leq 100\ mm$.
- **Liner design service life (t) -** The platform will calculate the minimum design liner thickness (T_L) based on the service life (time in years) examined. Units are in years. $0 \leq t \leq 100\ years$.

Advanced parameters are based on generic liner properties, which are explained in the theory manual (TM M4 Part 1 – Determination of liner long-term properties, TM Part 2 – Lined pipe analysis and product standards available from WSAA), were found from literature and Monash University testing (Figure 4).

Generic liner parameters were developed from the testing regime conducted at Monash University and are shown below.

Table 1 shows the short-term generic liner properties used in the Platform. These properties were found from tensile testing, flexural testing and thermal expansion testing. Table 2 shows the long-term generic liner properties from creep rupture/hydrostatic design basis testing and creep. Table 3 shows the fatigue properties from fatigue testing used in the Platform. For further details on how to use the long-term deterioration coefficients (Table 2 and Table 3) please see TM M4 Part 1 – Determination of liner long-term properties.

Table 1. Generic short-term liner properties for liner type and class

		Tensile strength (MPa)		Tensile modulus (GPa)		Flexural strength (MPa)		Flexural modulus (GPa)		Poisson's ratio	Thermal coefficient (mm/mm/°C)[2]
Liner	Class	σ_{th}	σ_{ta}	E_{th}	E_{ta}	σ_{fh}	σ_{fa}	E_{fh}	E_{fa}	ν_L	α
CIPP	C[3]	45	30	0.4	0.07	0	0	0	0	0.5	0.00005
CIPP	B	75	50	3	2	40	40	2	2	0.31	0.00005
CIPP	A	75	65	6	5	60	60	6	5	0.31	0.00005
Spray	A-D	35	35	3	3	60	60	3	3	0.35	0.00005

Table 2. Generic long-term liner properties for liner type and class

		Strength reduction coefficients (hoop)		Coefficients for creep modulus reduction (axial)		Coefficients for creep modulus reduction (hoop)	
Liner	Class	x_l	c_l	x_{lc}	c_{lc}	x_{lc}	c_{lc}
CIPP	C	-0.017	0.78	1	-0.106	0.88	-0.14
CIPP	B	-0.017	0.78	1.5	-0.17	1.1	-0.12
CIPP	A	-0.017	0.78	1.5	-0.17	1.1	-0.12
Spray	A-D	-0.03	0.65	2.16	-0.278	2.16	-0.278

Table 3. Generic fatigue long-term liner properties for liner type

	Coefficients for fatigue strength reduction (hoop)	
Liner type/reinforcement type	x_f	c_f
Spray	-0.0368	1.023
GFRP	-0.0493	1.146
FRP	-0.0133	0.946

Figure 4 shows the user interface for advanced liner properties. The advanced parameters are gathered from the generic liner properties (Table 1, Table 2, and Table 3). Users can modify these advanced parameters based on their preferred liner.

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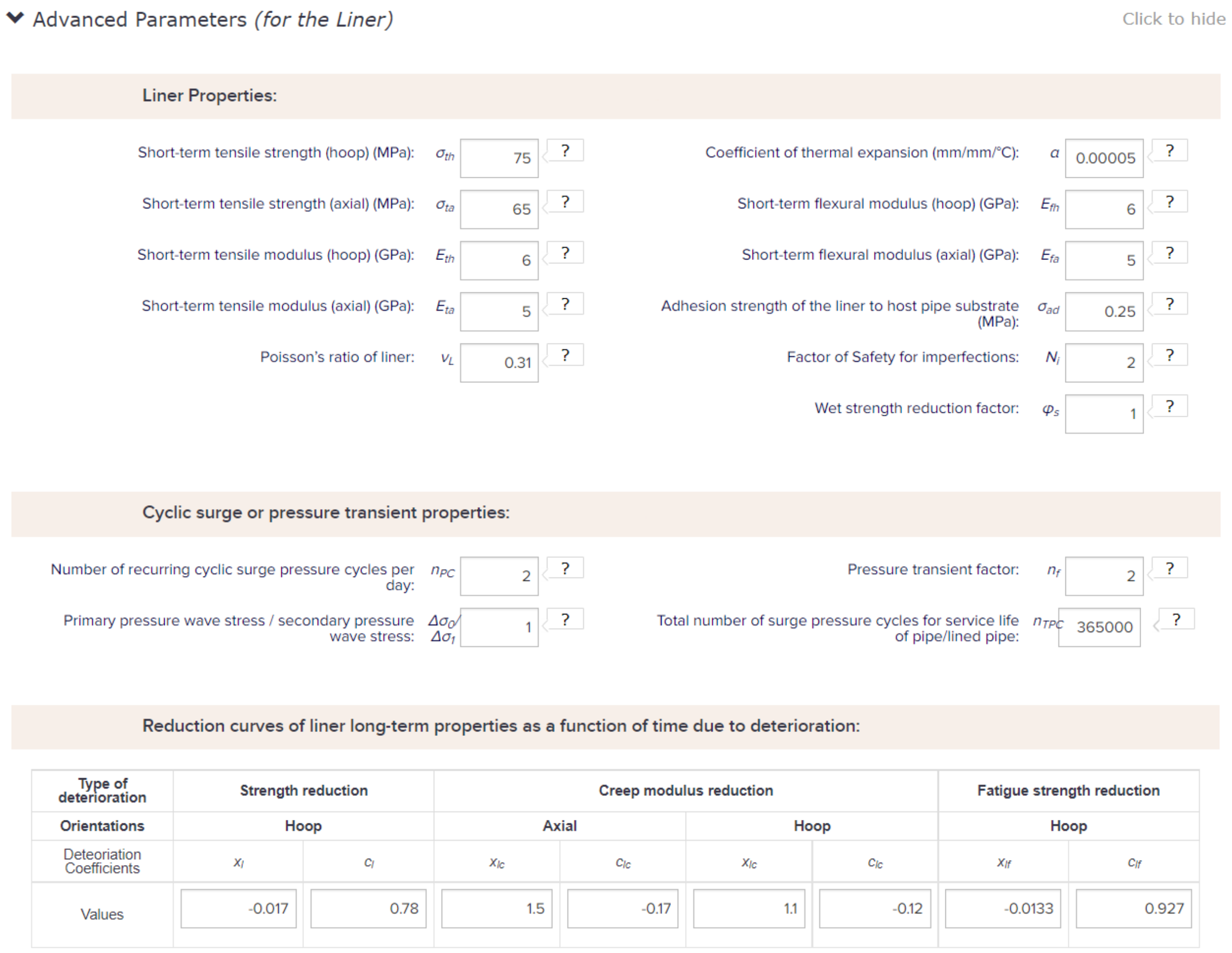
[2] Note: Coefficient of thermal expansion values have been approximated from literature. Property testing still needs to be conducted.

[3] Flexural strength and modulus of Class C CIPP liner were based on a flexible liner (highly ductile resin), hence no flexural strength was recorded.



Advanced Parameters *(for the Liner)*

Click to hide

Liner Properties:

Short-term tensile strength (hoop) (MPa): σ_{th} 75 ?
Short-term tensile strength (axial) (MPa): σ_{ta} 65 ?
Short-term tensile modulus (hoop) (GPa): E_{th} 6 ?
Short-term tensile modulus (axial) (GPa): E_{ta} 5 ?
Poisson's ratio of liner: ν_L 0.31 ?
Coefficient of thermal expansion (mm/mm/°C): α 0.00005 ?
Short-term flexural modulus (hoop) (GPa): E_{fh} 6 ?
Short-term flexural modulus (axial) (GPa): E_{fa} 5 ?
Adhesion strength of the liner to host pipe substrate (MPa): σ_{ad} 0.25 ?
Factor of Safety for imperfections: N_i 2 ?
Wet strength reduction factor: φ_s 1 ?

Cyclic surge or pressure transient properties:

Number of recurring cyclic surge pressure cycles per day: n_{PC} 2 ?
Primary pressure wave stress / secondary pressure wave stress: $\Delta\sigma_0 / \Delta\sigma_1$ 1 ?
Pressure transient factor: n_f 2 ?
Total number of surge pressure cycles for service life of pipe/lined pipe: n_{TPC} 365000 ?

Reduction curves of liner long-term properties as a function of time due to deterioration:

Type of deterioration	Strength reduction		Creep modulus reduction				Fatigue strength reduction	
Orientations	Hoop		Axial		Hoop		Hoop	
Deteoriation Coefficients	x_l	c_l	x_{lc}	c_{lc}	x_{lc}	c_{lc}	x_{lf}	c_{lf}
Values	-0.017	0.78	1.5	-0.17	1.1	-0.12	-0.0133	0.927

Figure 4. Advanced parameter for liner selection. Values are prefilled based on the basic mode options selected by the user.

- **Short-term tensile strength of the liner (σ_t, σ_{th} and σ_{ta}) -** Short-term (initial) tensile strength of the liner (from wet testing – testing conducted with saturated specimens) is the ultimate tensile strength of the liner. Testing is conducted in both axial and hoop directions (if liner is bi-directional, where subscript *h* is in the hoop direction and subscript *a* is in the axial direction). Testing is conducted from tensile tests (AS 1145 2001, ASTM D638 2014, ASTM D3039 2017) and units are in MPa. $5 \le \sigma_t \le 500\ MPa$.

- **Short-term tensile modulus of elasticity of the liner (E_L, E_t, E_{th} and E_{ta}) -** Short-term (initial) tensile modulus of elasticity or Young's modulus of the liner (from wet testing – testing conducted with saturated specimens) is the stress divided by strain of the linear proportion of the stress strain curve. Testing is conducted in both axial and hoop directions (if liner is bidirectional, where subscript *h* is in the hoop direction and subscript *a* is in the axial direction). Testing is conducted from tensile tests (AS 1145 2001, ASTM D638 2014, ASTM D3039 2017) and units are in GPa. $0.01 \le E_L \le 100\ GPa$.

- **Poisson's ratio of the liner (ν_L) -** Poisson's ratio is the measurement of deformation in pipe liner material in a direction perpendicular to the direction of the applied force. Units are dimensionless. $0.1 \le \nu_L \le 0.5$.

- **Coefficient of thermal expansion (α) -** Coefficient of thermal expansion or contraction is the change in size with change in temperature. The units are in mm/mm/°C. $0 \le \alpha \le 0.01$ mm/mm/°C.

- **Short-term flexural modulus of elasticity of the liner (E_{fh} and E_{fa}) -** Short-term (initial) tensile modulus of elasticity or Young's modulus of the liner (from wet testing – testing conducted with saturated specimens) is the stress divided by strain of the linear proportion of the stress strain curve.

Testing is conducted in both axial and hoop directions (if liner is bidirectional, where subscript *h* is in the hoop direction and subscript *a* is in the axial direction). Testing is conducted from flexural tests (ISO 14125 (1998), (AS 1145 2001, ASTM D790 2017) and units are in GPa. $0.01 \leq E_f \leq 100\ GPa$.

- **Adhesion strength of the liner to host pipe substrate (σ_{ad}) -** Adhesion strength of the liner to host pipe substrate. Adhesion tested on a variety of surfaces, including CML (if CML lined pipe) shall be determined using any or all of the following standards: ASTM D4541 for metal, ASTM D7234 for AC and CML, or Pull off adhesion testing to AS 3894.9 for all CIPP classes that require adhesion for sealing (e.g. at ends or service connections) or bonding to the host pipe (Class C). Units are in MPa. $0 \leq \sigma_{ad} \leq 100\ MPa$.
- **Factor of safety for liner imperfections (N_i) -** Factor of safety for liner imperfections (variable wall thickness in polymeric spray lining and folds in CIPP lining), depends on the imperfection type. The following factors of safety for liner imperfections were selected:
    - Uneven thickness (polymeric spray), $N_i = 1.5$
    - Folds (CIPP), $N_i = 2$
- **Wet strength reduction factor (ϕ_s) -** If the liner is subjected to plasticisation due to water saturation a wet strength reduction factor must be applied to reduce short-term and long-term strength properties. Ideally, testing should be conducted in wet conditions if liner plasticises when saturated. This is more common in polymeric spray liners than CIPP liners. The wet factor reduction ranges from 0.5–1, however the default value is set as 1 in the Monash Pipe Evaluation Platform as the tests are assumed to be conducted in water.

  For example:

$$\phi_s = \frac{\sigma_{t,wet}}{\sigma_{t,dry}}$$

  where $\sigma_{t,wet}$ is the wet tensile strength of the liner (MPa) and $\sigma_{t,dry}$ is the dry tensile strength of the liner (MPa). These properties can be interchanged with σ_{th} and σ_{ta} if property tests were conducted in water. The use of tensile/flexural and hoop/axial shall be consistent for both wet and dry properties to determine strength reduction factors. $0.5 \leq \phi_s \leq 1$.
- **Number if recurring cyclic surge pressure cycles (cycles/day) (n_{PC}) -** Number of pressure transients per day are used to determine if the host pipe or liner will fail from fatigue. Consistent pressure transients may reduce the life of the host pipe and liner. The default value is set at 2 per day, for pump start-up and pump shutdown. $0 \leq n_{PC} \leq 100$ cycles per day.
- **Primary pressure wave stress / secondary pressure wave stress ($\Delta\sigma_0/\Delta\sigma_1$)** - The magnitude of the initial pressure cycle wave stress ($\Delta\sigma_0$) divided by the magnitude of the secondary pressure cycle wave stress ($\Delta\sigma_1$). See Figure 5 for further details. A value of 1 indicates the second pressure wave is as large as the first and is conservative. $0 \leq \Delta\sigma_0/\Delta\sigma_1 \leq 5$.

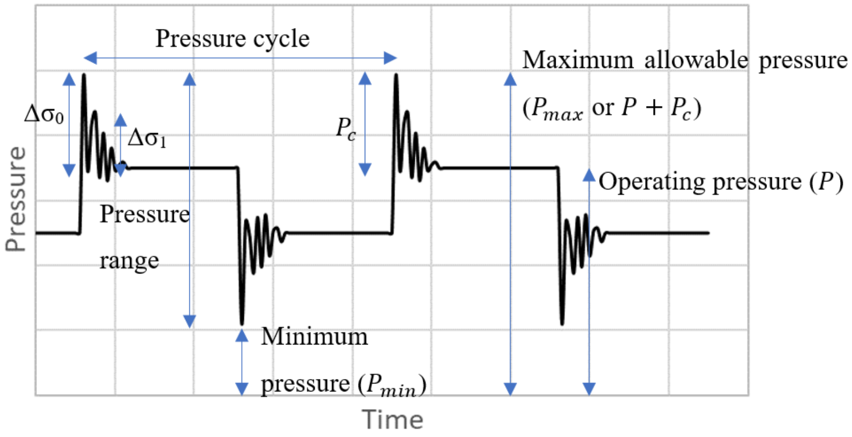


Figure 5. Pressure information used in the MPEP.

- **Cyclic surge factor (n_f)** - A surge factor (n_f) or pressure transient factor is used to incorporate the effect of secondary cycles from cyclic surge pressure. A simplistic approach is to use a pressure cycle is equal to 2 primary cycles due to the decaying surge. Alternatively, the following equations can be used to calculate a factor for number of pressure transients (Joseph 1979, PIPA 2018).

  $$n_f = 1 + \frac{1}{\left(\frac{\Delta\sigma_0}{\Delta\sigma_1}\right)^{3.2}}$$

  where n_f is the cyclic surge factor (from 1 to 2), $\Delta\sigma_0$ is the magnitude of the initial pressure cycle wave and $\Delta\sigma_1$ is the magnitude of the secondary pressure cycle.

- **Total number of pressure transients for the life of the pipe/lined pipe (n_{TPC})** - The total number of pressure transients or cyclic pressure surges can be calculated based on the following equation

  $$n_{TPC} = n_{PC} \times n_f \times t \times 365$$

  where n_f is the cyclic surge factor (from 1 to 2) and t is the time in years, where in this case is the liner design service life in years. $0 \leq n_{TPC} \leq 10^7$.

- **Tensile rupture strength of the liner ($\sigma_{tl,r}$, $\sigma_{thl,r}$ and $\sigma_{tal,r}$)** - Tensile rupture strength or long-term tensile strength (hoop or axial) of the liner at *x* years is based on creep rupture (ASTM D2990 2001) or hydrostatic design basis (ASTM D2992 2018) for a specified design life (years). The normalised curve can be multiplied by the initial tensile strength in MPa. Wet conditions should be used.

  The following equation is used to approximate the deterioration curve based on hydrostatic design basis or creep rupture testing. The equation uses the 97.5% lower prediction limit results, to account for variability in the results and is simplified to a logarithmic curve. Alternatively, the hydrostatic design stress value can be used if the service life is 50 years.

  $$\sigma_{tl,r} = \sigma_t(x_l ln(t_h) + c_l)$$

  where, $\sigma_{tl,r}$ is the tensile rupture strength at a particular service life (σ_{tl} can be substituted for $\sigma_{thl,r}$ and $\sigma_{tal,r}$ for the hoop and axial values respectively), σ_t is the short-term tensile strength (σ_t can be substituted for σ_{th} and σ_{ta} for the hoop and axial values respectively), x_l and c_l are creep rupture deterioration constants and t_h is the time in hours.

  Note: The same formula can be applied to approximate the long-term flexural strength by substituting short-term wet flexural strength values, however flexural creep rupture testing is preferred.

- **Coefficient for strength reduction (x_l)** - Deterioration coefficient for creep rupture or hydrostatic design basis normalised stress vs. time (hours) curve. Will be a negative value to correspond with rupture strength of the liner.

- **Coefficient for strength reduction (c_l)** - Deterioration coefficient for creep rupture or hydrostatic design basis normalised stress vs. time (hours) curve. Will be a positive number.

- **Tensile creep modulus of the liner (E_{tl}, E_{thl} and E_{tal})** - Creep modulus (hoop or axial) is defined as the ratio of applied stress to the time-dependent strain and is determined based on creep testing (ASTM D2990 2001) or hydrostatic strain basis (ASTM D2992 2018) for a specified design life (years). Wet conditions should be used.

  The tensile creep modulus (E_{tl}) was estimated using Findley's power law from creep tests up to 20,000 hours and extrapolated up to 100 years. The creep modulus in tensile and axial can be found by multiplying the corresponding creep retention factor (CRF) by the initial or short-term modulus.

  $$E_{tl} = CRF \cdot E_t$$

  where E_{tl} is the tensile creep modulus and E_t is the short-term tensile modulus. The following equation can be used to determine the CRF and subsequently the long-term tensile modulus at any point in time.

  $$CRF = x_{lc}(t_h)^{c_{lc}}$$

  where x_{lc} and c_{lc} are factors to determine creep modulus factor based on a power law decay, and t_h is the time in hours.

Note: The same formula can be applied to approximate the flexural creep modulus by substituting short-term wet flexural strength values, however flexural creep testing is preferred. This formula should not be used for less than 100 hours.

- **Creep retention factor (CRF) -** The creep retention factor (CRF) is the creep modulus divided by the initial or short-term modulus of the liner (in either hoop or axial directions).

$$CRF = \frac{E_{tl}}{E_t}$$

- **Deterioration coefficient for creep (x_{lc}) -** Deterioration coefficient for creep modulus vs. time (hours) curve based on testing results and Findley's power law. Will be a positive number.
- **Deterioration coefficient for creep (c_{lc}) -** Deterioration coefficient for creep modulus vs. time (hours) curve based on testing results and Findley's power law. Will be a negative number.
- **Fatigue strength (hoop) of the liner ($\sigma_{thl,f}$) -** Fatigue strength or long-term tensile fatigue deterioration strength (hoop) at *x* years is based on fatigue curves based on ISO 13003 (2003) or cyclic pressure design basis (ASTM D2992 2018) for a specified design life (years). The normalised stress vs. number of cycles to failure (N_f) curve can be multiplied by the initial tensile strength in MPa. Wet conditions should be used.

  The following equation is used to approximate the deterioration curve based on cyclic pressure design basis or fatigue cyclic testing. The equation uses the 95% lower prediction limit results, to account for variability in the results and is simplified to a logarithmic curve. Alternatively, the hydrostatic fatigue stress value can be used if the service life is 50 years.

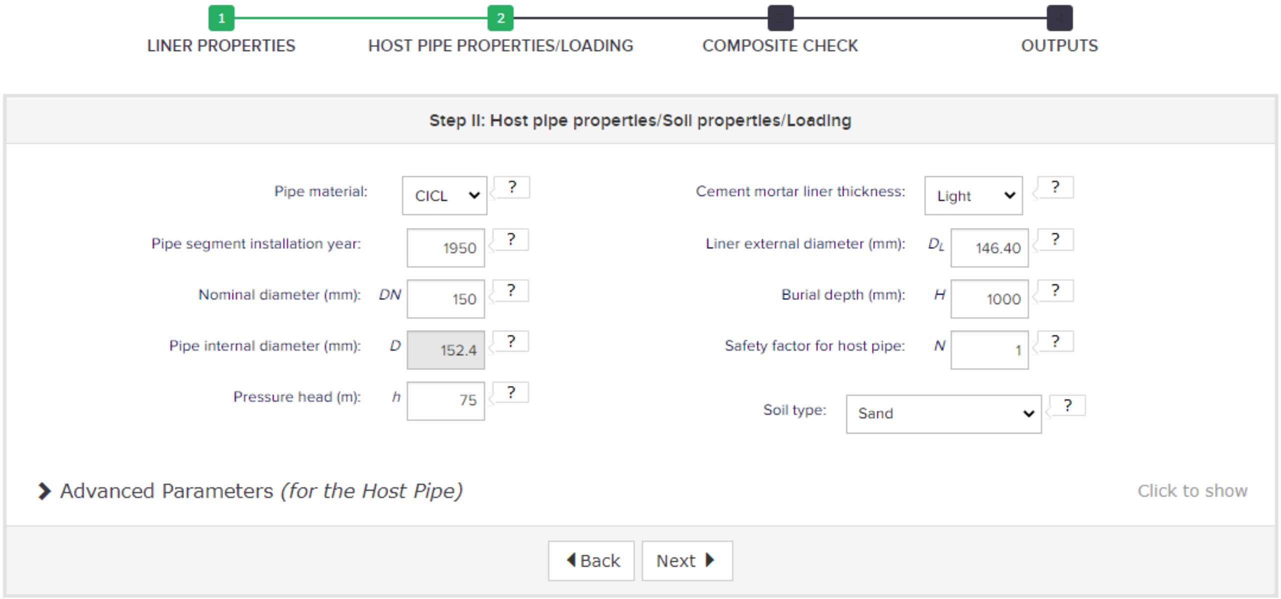
$$\sigma_{thl,f} = \sigma_{th}\left(x_{lf} ln(n_{TPC}) + c_{lf}\right)$$

  where, $\sigma_{thl,f}$ is the long-term fatigue strength at a particular service life, σ_{th} is the (wet) short-term tensile strength, x_{lf} and c_{lf} are fatigue deterioration constants and n_{TPC} is the total number of surge pressure cycles for life of pipe/lined pipe.

- **Coefficient for fatigue strength reduction (x_{lf}) -** Deterioration coefficient for fatigue or cyclic pressure design basis normalised stress vs. time (hours) curve. Will be a negative value to correspond with deteriorated strength of the liner.
- **Coefficient for fatigue strength reduction (c_{lf}) -** Deterioration coefficient for fatigue or cyclic pressure design basis normalised stress vs. time (hours) curve. Will be a positive number.

1.2 Step II – Host pipe properties/soil properties/loading

Implementing the host pipe properties are similar to the other modules (Module 2 and 3, pipe failure analysis and liner selection respectively), where host pipe properties are gathered from pipe cohorts (see TM M2 Part 1 – Pipe and soil cohorts). The properties are prefilled based on the pipe material, pipe segment installation year, nominal diameter and operating pressure. The properties are shown in Figure 6.



Step II: Host pipe properties/Soil properties/Loading

Pipe material: CICL

Pipe segment installation year: 1950

Nominal diameter (mm): DN 150

Pipe internal diameter (mm): D 152.4

Pressure head (m): h 75

Cement mortar liner thickness: Light

Liner external diameter (mm): D_L 146.40

Burial depth (mm): H 1000

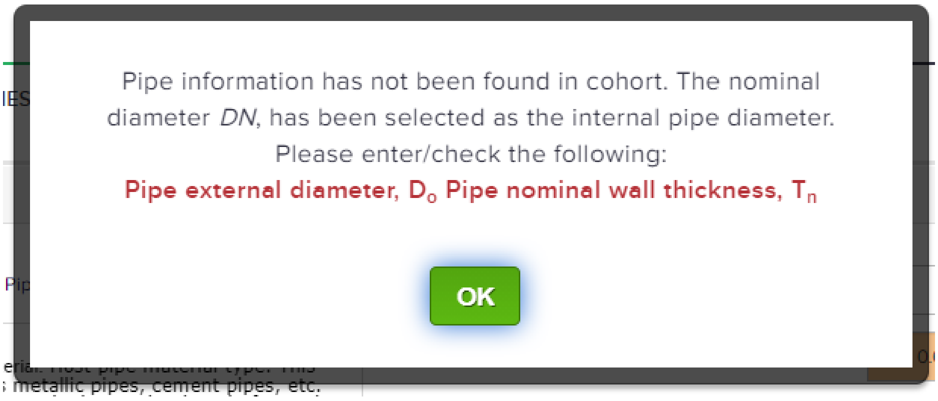
Safety factor for host pipe: N 1

Soil type: Sand

Advanced Parameters *(for the Host Pipe)* Click to show

Figure 6. User inputs host pipe properties/Soil properties/loading

The host pipe will be assigned a standard based on the pipe segment installation year, and an internal diameter based on the pressure head (operating pressure). Users can increase the pressure head value if the pipe class is higher (larger wall thickness). A warning will appear if the pipe properties are not found in the cohort (Figure 7). This can arise if the nominal diameter is not close to the ones found in standards or operating pressure is high.



Pipe information has not been found in cohort. The nominal diameter *DN*, has been selected as the internal pipe diameter. Please enter/check the following:

Pipe external diameter, D_o Pipe nominal wall thickness, T_n

Figure 7. Warning when cohort information cannot be found.

- **Pipe material -** Host pipe material type. This includes metallic pipes, cement pipes, plastic pipe, etc. In the Monash Pipe Evaluation Platform, the following pipe materials are implemented: Cast Iron (CI, CICL), Asbestos cement (AC), Mild Steel (MS, MSCL) and Ductile Iron (DICL).
- **Pipe segment installation year -** Construction year of the pipe, burial year of the pipe or pipe installation year. 1800 to 2021.
- **Pipe nominal diameter (DN) -** 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). Note that in some pipes, such as AC the pipe outer diameter (OD or D_0) remains constant to allow for fitting compatibility, inner diameter reduces with an increase in pressure Class (wall thickness). 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. $50 \leq DN \leq 3000$ mm.

- **Pipe internal diameter (D) -** Pipe internal diameter is the internal diameter of the host pipe, not including liners (e.g. CML). Internal diameter is found from pipe cohorts and standards, however the pipe nominal diameter (DN) can also be used as an approximation if internal diameter is unknown. The internal diameter units are expressed in mm. Figure 8 shows the different terms used in pipe.

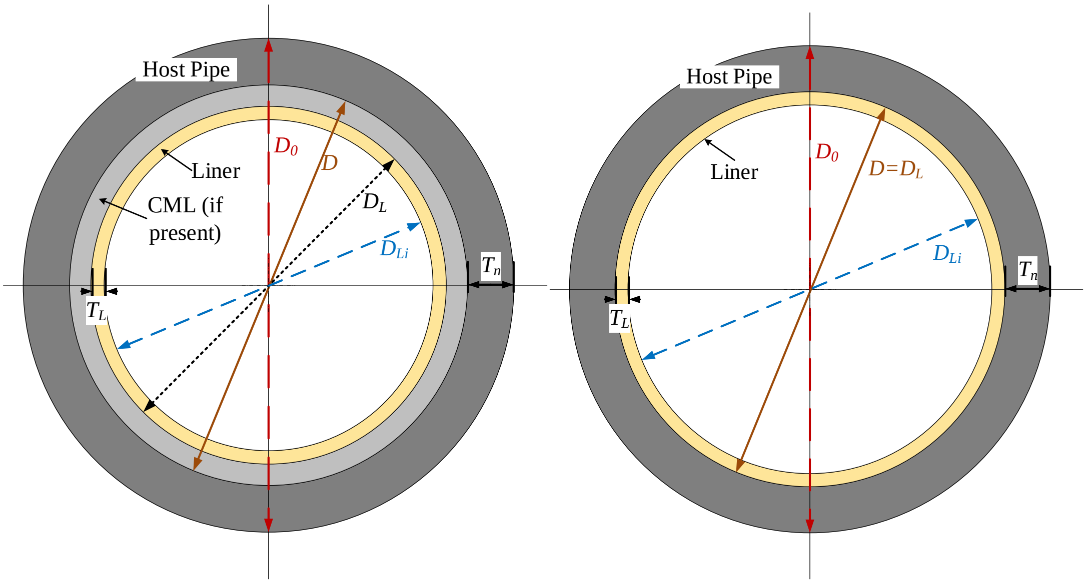
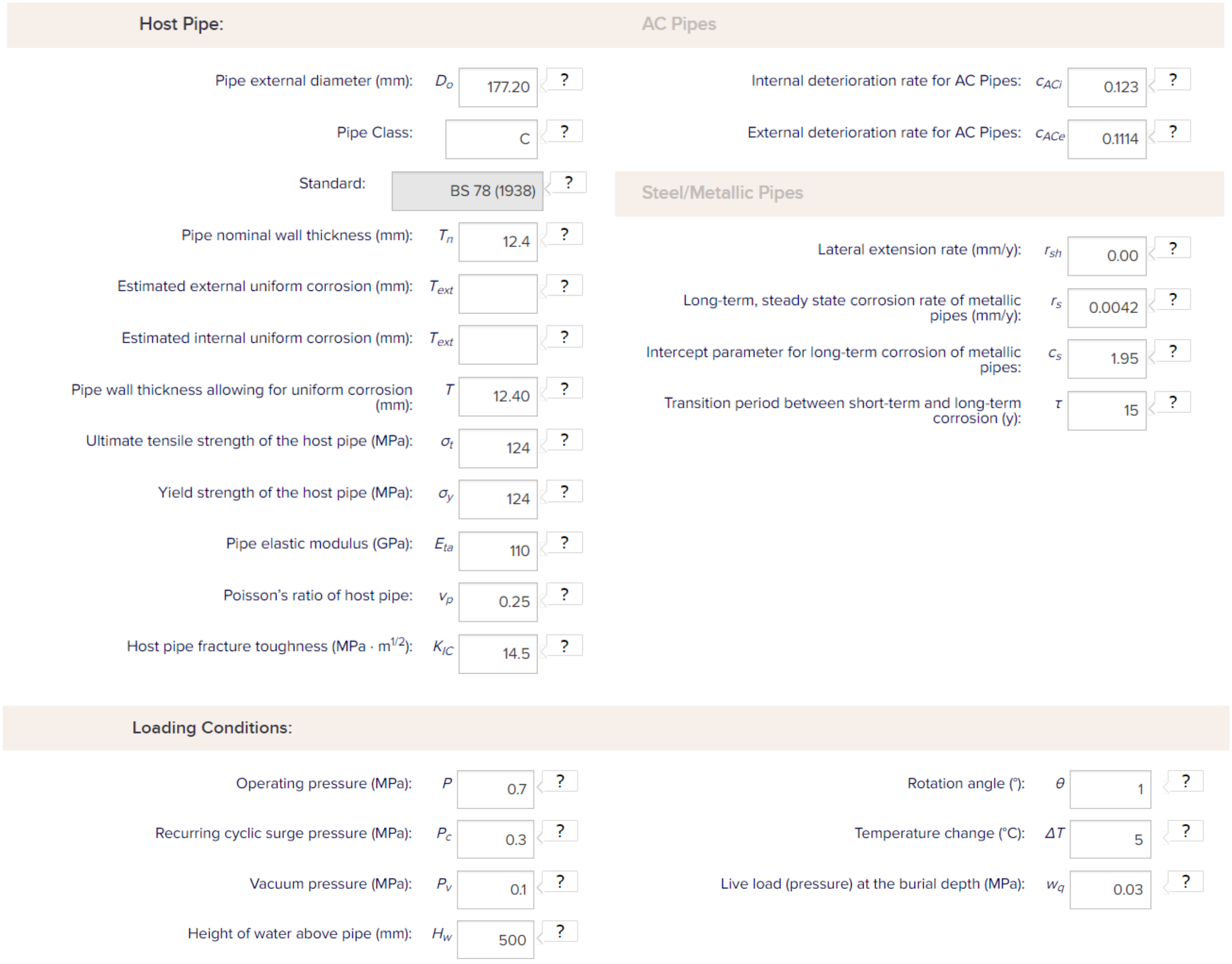


Figure 8. Labelling of pipe and liner term, left with CML, right without CML

- **Pressure head (h) -** The operating pressure converted to a meter head value. Used to determine the pressure class of the pipe. Units are in m. $0 \leq h \leq 300$ m.
- **Cement mortar liner thickness –** Cement mortar liner (CML) thickness, which can be either *in situ* or factory lined. Options include Light, Medium and Heavy. For use with CL pipes only.
- **Liner external diameter (D_L) –** The liner external diameter in mm. The liner external diameter can be equal to the pipe internal diameter (D) if no CML is present. If a CML is present, D and D_L need to be used for calculation. See Figure 8. $0 \leq D_L \leq 5000$ mm.
- **Burial depth (H) -** The depth of the pipe from the ground surface level to the crown of the pipe Units are in mm. $0 \leq H \leq 10000$ mm.
- **Safety factor for host pipe (N) –** A safety factor for host pipe. A value of 1 indicates no factor of safety. $1 \leq N \leq 5$.
- **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.

If further information is required to be changed by the user, the Advanced parameters tab can be selected (Figure 9). The host pipe properties including material properties and sizes (gathered from cohort data – See Theory manual Pipe and soil cohorts) can be modified as well as soil properties (gathered from soil cohort data). The soil type dropdown box will automatically change the soil properties values in the advanced parameters tab.



Host Pipe:

Pipe external diameter (mm):	D_o	177.20
Pipe Class:		C
Standard:		BS 78 (1938)
Pipe nominal wall thickness (mm):	T_n	12.4
Estimated external uniform corrosion (mm):	T_{ext}	
Estimated internal uniform corrosion (mm):	T_{ext}	
Pipe wall thickness allowing for uniform corrosion (mm):	T	12.40
Ultimate tensile strength of the host pipe (MPa):	σ_t	124
Yield strength of the host pipe (MPa):	σ_y	124
Pipe elastic modulus (GPa):	E_{ta}	110
Poisson's ratio of host pipe:	ν_p	0.25
Host pipe fracture toughness (MPa · m$^{1/2}$):	K_{IC}	14.5

AC Pipes

Internal deterioration rate for AC Pipes:	c_{ACi}	0.123
External deterioration rate for AC Pipes:	c_{ACe}	0.1114

Steel/Metallic Pipes

Lateral extension rate (mm/y):	r_{sh}	0.00
Long-term, steady state corrosion rate of metallic pipes (mm/y):	r_s	0.0042
Intercept parameter for long-term corrosion of metallic pipes:	c_s	1.95
Transition period between short-term and long-term corrosion (y):	τ	15

Loading Conditions:

Operating pressure (MPa):	P	0.7
Recurring cyclic surge pressure (MPa):	P_c	0.3
Vacuum pressure (MPa):	P_v	0.1
Height of water above pipe (mm):	H_w	500
Rotation angle (°):	θ	1
Temperature change (°C):	ΔT	5
Live load (pressure) at the burial depth (MPa):	w_q	0.03

Figure 9. Advanced properties for host pipe and soil

- **Pipe external diameter (D_0)** - External diameter of the host pipe, also known as pipe outside diameter (OD), not including external coatings (e.g. bitumen). Pipe external diameter can be found from pipe cohorts and standards. The external diameter units are expressed in mm. See Figure 8. $50 \leq D_0 \leq 5000$ mm.
- **Pipe pressure class** - Pipe pressure class designed to withstand a certain pressure over a certain number of years. A safety factor would be included. Pipe pressure class can be used to gather pipe wall thickness, which are used in determining remaining life of the host pipe. Pipes with a higher-pressure class, have a larger wall thickness to withstand higher internal pressures. Typically, pressure classes are expressed as A to D for cast iron pipes and A to F for Asbestos cement pipes.
- **Standard -** Standard that pipe cohort values have been used from.
- **Pipe nominal wall thickness ()** – The original wall thickness of the pipe (Figure 4). Units are in mm. $T_n > 0$.
- **Pipe nominal wall thickness (T_n) -** The original wall thickness of the pipe (Figure 10). Units are in mm. $T_n > 0$.
- **Estimated external uniform corrosion (T_{ext}) -** the pipe wall thickness reduction caused by external corrosion (Figure 10). Units are in mm. $0 < T_{ext} < T_n$.
- **Estimated internal uniform corrosion (T_{int}) -** the pipe wall thickness reduction caused by internal corrosion (Figure 10). Units are in mm. $0 < T_{int} < T_n - T_{ext}$.

- **Pipe wall thickness allowing for uniform corrosion (T) -** the actual pipe wall thickness after accounting for external and internal corrosion (Figure 10). Units are in mm. Note that $\boldsymbol{T = T_n - T_{ext} - T_{int}}$.

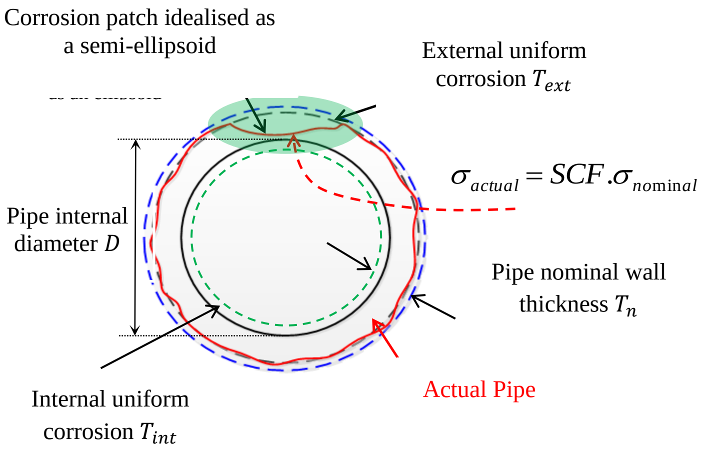


Figure 10. Cross section of a corroded pipe

- **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. $0 < \sigma_t \leq 1000\ MPa$.
- **Yield strength $\boldsymbol{\sigma_y}$**: also known as specified minimum yield strength ($SMYS$) is the stress corresponding to the yield point at which the material begins to deform plastically. Units are in MPa. $0 < \sigma_y \leq 1000\ MPa$.
- **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. $1 \leq E_p \leq 150$ GPa.
- **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. $0.1 \leq v_p \leq 0.4$.
- **Fracture toughness $\boldsymbol{K_{IC}}$**: the resistance of materials to the propagation of cracks under an applied stress. Units are in $\mathrm{MPa}\sqrt{m}$. $0 < \boldsymbol{K_{IC}} \leq 100\ \mathrm{MPa}\sqrt{m}$**.**
- **Internal deterioration rate for AC pipes ($\boldsymbol{c_{ACi}}$) -** Internal deterioration rate for AC pipes. Rates can be calculated from phenolphthalein testing or approximated based on utility data. Units are in mm/y. $0 \leq c_{ACi} \leq 0.5$ mm/y.
- **External deterioration rate for AC pipes ($\boldsymbol{c_{ACe}}$) -** External deterioration rate for AC pipes. Rates can be calculated from phenolphthalein testing or approximated based on utility data. Units are in mm/y. $0 \leq c_{ACe} \leq 0.5$ mm/y.
- **Lateral extension rate $\boldsymbol{r_{sh}}$**: 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. $\boldsymbol{0 \leq r_{sh}}$**.**
- **Long-term corrosion rate $\boldsymbol{r_s}$:** the long-term steady state corrosion rate of metallic pipes (mm/year) in the exponential corrosion model (Figure 11).

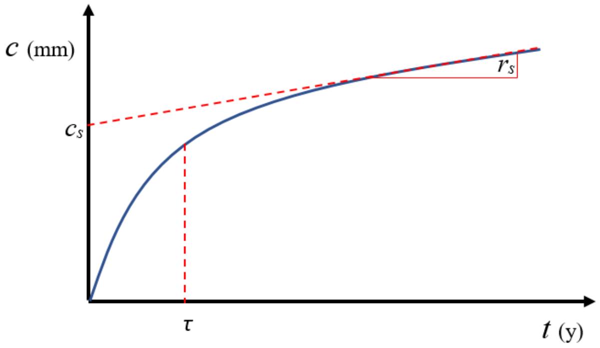


Figure 11. Exponential corrosion model

- **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 (Figure 11).
- **Transition period between short-term and long-term corrosion τ:** 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 (Figure 11).
- **Soil modulus 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. $\mathbf{0 < E_s \leq 300\ MPa}$**.**
- **Lateral earth pressure coefficient:** the lateral earth pressure coefficient at rest and can be calculated by:

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

where ∅ is the soil friction angle. $\mathbf{0 \leq k \leq 1}$**.**

- **Soil unit weight γ_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. $\mathbf{0 < \gamma_s \leq 30}$ **kN/m^3.**
- **Operating pressure P:** the operating pressure or maximum work/working pressure is the maximum internal pressure sustained that the liner is anticipated to be subjected to, including diurnal pressure fluctuations but not including recurring cyclic surge pressure (Figure 12). Units are in MPa. $\mathbf{0 \leq P \leq 3}$ **MPa.**

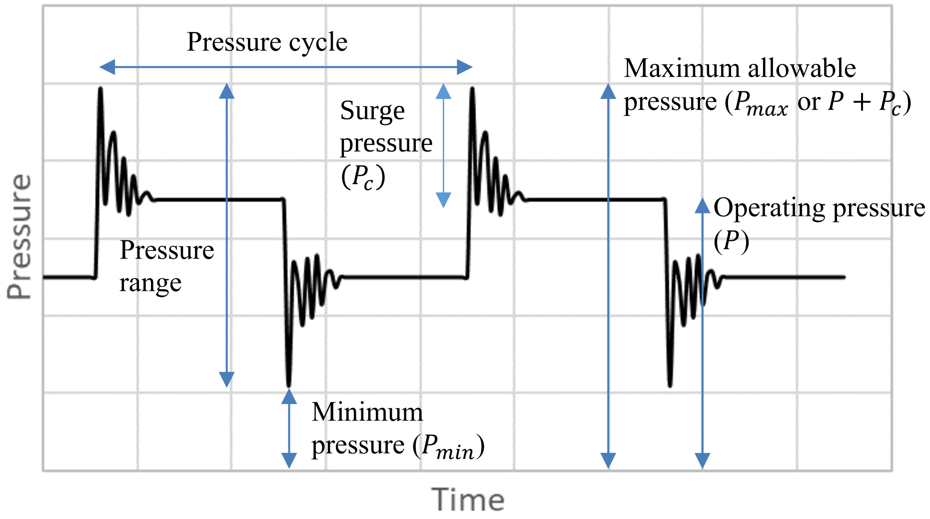
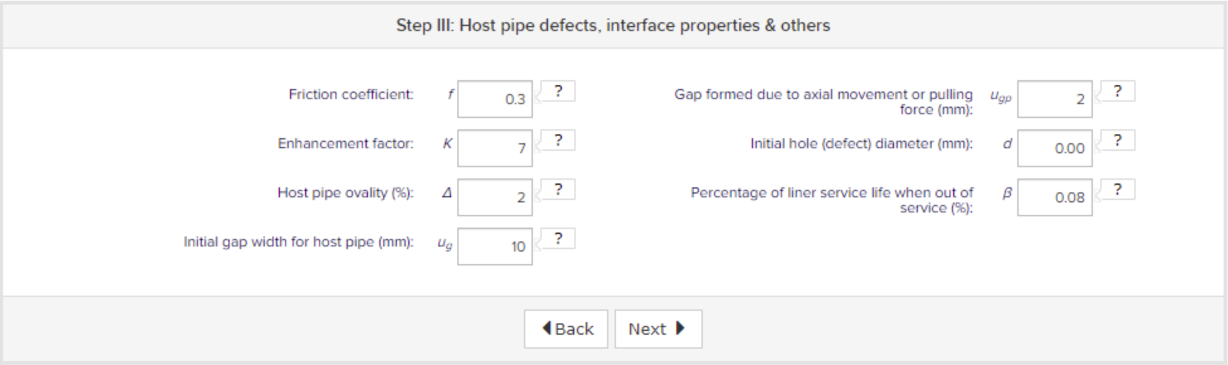


Figure 12. Types of pressures

- **Recurring cyclic surge pressure** (P_c) - Frequent repetitive pressure variations or cyclic surge pressures (water hammer) that are common in pressure pipe network systems (pump start-up or shut-down and normal valve opening and closings) (Figure 12). Units are in MPa. **$0 \le P_c \le 1$ MPa.**
- **Vacuum pressure (P_v) -** A negative pressure that a pipe may experience when subjected to a sudden displacement in water, such as dewatering, which results in a vacuum pressure. Vacuum pressure ranges from 0 MPa (no vacuum) to 0.1 MPa (high vacuum). If pipe is subjected to vacuum loading a suggested value of 0.1 MPa is used in the Monash Pipe Evaluation Platform. Units are in MPa. **$0 \le P_v \le 0.1$ MPa.**
- **Height of water above pipe, measured from pipe crown** (H_w) - Height of water above pipe, measured from pipe crown is the depth of the groundwater to the crown of the pipe. Units are in mm. Groundwater can apply additional pressure on the outer pipe wall. Groundwater depth in the form of pressure is used for pipe failure analysis and lined pipe analysis. **$0 \le H_w \le 10000$ mm.**
- **Rotation angle (θ) -** Rotation angle that the lined pipe is likely to rotate to if a broken back failure occurs in the host pipe. Units are in degrees (°). Used in determining the gap spanning under ring fracture or damaged failed joints under internal pressure. **$0 \le \theta \le 5$ °.**
- **Temperature change (ΔT) -** The temperature change, fluctuations or maximum range of temperature expected to occur in the host pipe and liner during service. The difference between the maximum and minimum temperature. Units are in °C. Used to calculate any thermal effects due to, such as expansion due to temperature increase. **$0 \le \Delta T \le 30$ °C.**
- **Live load (pressure) at the burial depth (w_q) -** Surface live load at the pipe burial depth based on calculations found in AS 2566.1 (1998). Live loads are used for host pipe remaining life calculations and liner life extension calculations. Units are in MPa. **$0 \le P_c \le 0.1$ MPa.**

1.3 Step III – Host pipe defects, interface properties and others

Step III involves the host pipe defects such as pipe ovality, initial gap with and gap width due to pulling effect and hole size. Interface properties include the friction coefficient and enhancement factor. Also included is the percentage of liner service life when out of service. Further details on how each of these parameters are used can be found in the theory manual (TM M4 Part 2 – Lined pipe analysis). Figure 13 shows the user interface for Step III.



Step III: Host pipe defects, interface properties & others

Friction coefficient: f 0.3
Enhancement factor: K 7
Host pipe ovality (%): Δ 2
Initial gap width for host pipe (mm): u_g 10
Gap formed due to axial movement or pulling force (mm): u_{gp} 2
Initial hole (defect) diameter (mm): d 0.00
Percentage of liner service life when out of service (%): β 0.08

Figure 13. Host pipe defects, interface properties and others

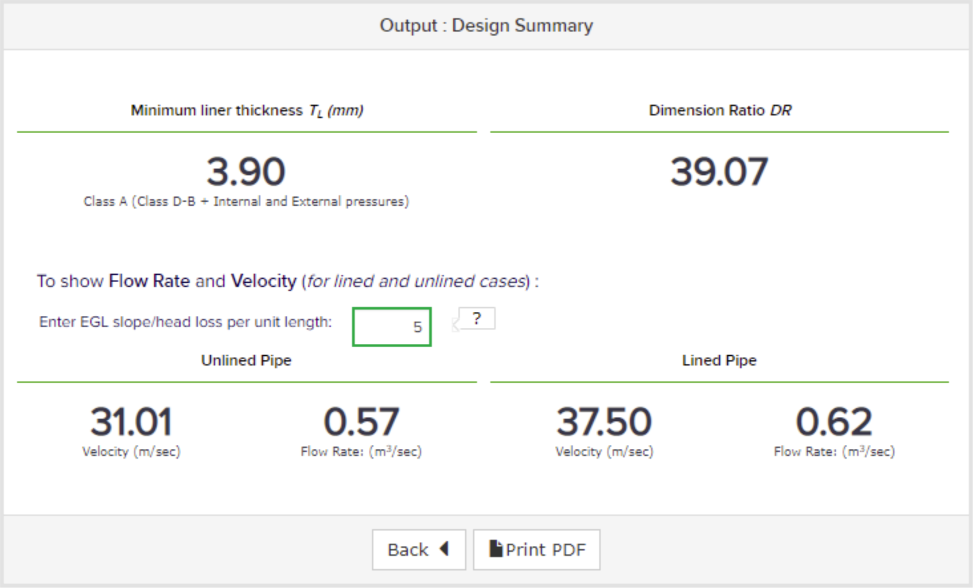
- **Friction coefficient (f)** - The friction between the liner and the host pipe (or CML). The friction coefficient ranges between 0 to 0.577 and depends on the adhesion of the liner to the host pipe (or CML). Units are dimensionless. The recommended ranges of friction coefficients for the interfaces between host pipes and polymeric liners are as follows:

Host pipe material	Friction coefficient (f)
AC or CML	0.1–0.2
Metallic	0.3–0.4

- **Enhancement factor (K) -** Enhancement factor of the soil and existing pipe adjacent to the new pipe; a minimum value of 7.0 is recommended where there is full support of the existing pipe (dimensionless) (AWWA 2019).
- **Host pipe ovality (Δ) -** Ovality is generally not a consideration for pressure pipe designs. However, when a pipe taken out of service is subjected to external pressures, ovality may be relevant. In absence of physical measurements, reasonable assumptions of ovality should be made based on host pipe material properties and in situ conditions. For example, ovality may never be observed on a rigid host pipe over the course of its design life, while a flexible pressure pipe may or may not ovalize (or deflect) when taken out of service (AWWA 2019). Units are percentage (%).
- **Ovality reduction factor (C) -** Ovality reduction factor is a reduction factor based on the liner ovality. The units are dimensionless.
- **Fraction of liner service life when out of service (β) -** The fraction of time a liner will be out of service. Used in determining if buckling of the liner may occur. Unitless. Typical values would range from 0.00005 (one day) to 0.0016 (one month).
- **Initial gap width of host pipe (u_g) -** Initial width of a gap in the host pipe, such as a gap at a joint, broken back failure, or where there is no host pipe, that a liner can span. Units are in mm.
- **Gap formed due to axial movement or pulling force (u_{gp}) -** Width of the gap formed in the host pipe, such as a gap at a joint, broken back failure, or where there is no host pipe when the host pipe is pulled along the longitudinal axis. Units are in mm.
- **Initial hole (defect) diameter (d) -** Initial hole or defect size (treat graphitised material as a defect), idealised to be circular in a metallic pipe. The units are in mm. Used in calculating hole spanning capability in a Class B to C liner.
- **Fraction of liner service life when out of service (β) -** The fraction of time a liner will be out of service. Used in determining if buckling of the liner may occur. Unitless. Typical values would range from 0.00005 (one day) to 0.0016 (one month).

1.4 Step IV – Outputs

In Step IV, the Platform uses all the data previously filled into the first three steps to calculate either the minimum liner thickness (mm) or the service life (years), depending on the initial selection in Step I. The calculations are performed using the equations for each of the seven (or 8 if AC host pipe) limit states (see TM M4 Part 2 – Lined pipe analysis), depending on the initial Class of liner selected. The results are shown in Figure 14. The user is able to input the energy grade line slope/head loss per unit length to determine the velocity and flow rate changes from installing a liner. The Hazen Williams equation is used (TM M4 Part 2 – Lined pipe analysis).



Output : Design Summary

Minimum liner thickness T_L *(mm)*

Dimension Ratio *DR*

3.90

Class A (Class D-B + Internal and External pressures)

39.07

To show **Flow Rate** and **Velocity** (*for lined and unlined cases*) :

Enter EGL slope/head loss per unit length: 5

Unlined Pipe

31.01 Velocity (m/sec)

0.57 Flow Rate: (m^3/sec)

Lined Pipe

37.50 Velocity (m/sec)

0.62 Flow Rate: (m^3/sec)

Figure 14. Outputs from the lined pipe analysis when designing for liner thickness

2 NPV COST ANALYSIS

The net present value (NPV) cost analysis sub module compares three options and computes the NPV cost over a period years of analysis. It uses information from the previous modules (pipe length – from pipe library and liner lifetime – from long-term analysis) and information to be entered by users.

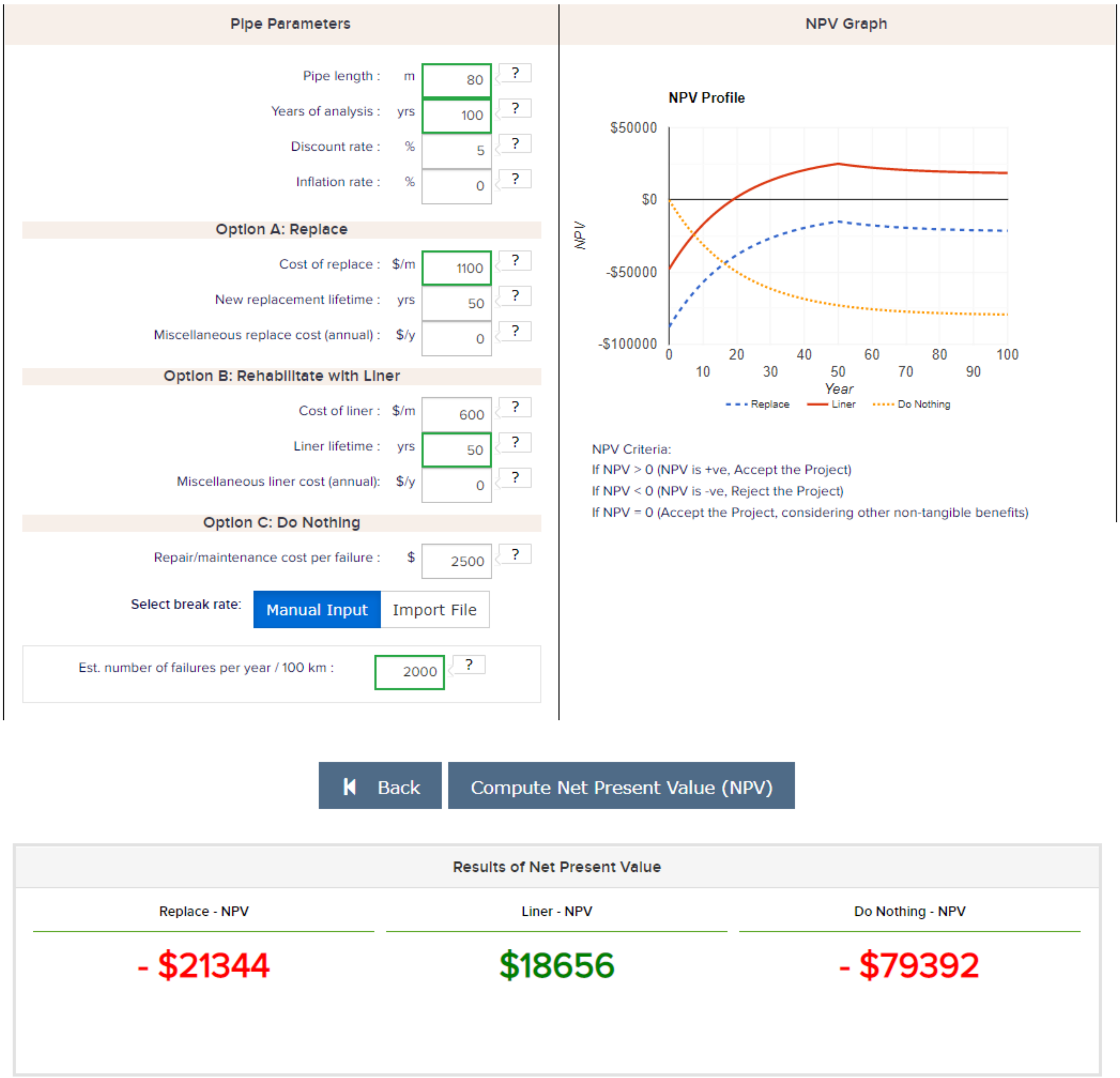
The three options include:

- Replace
- Rehabilitate with liner
- Do nothing

Pipe parameters needed for calculations are: length of pipe, L_p (m), years of analysis (yrs), discount rate, i (%) and inflation rate, IN (%). For each of the options the users need to input the cost per meter (rates should be either found from water utilities or contractors), the pipe or liner lifetime, and the miscellaneous/maintenance cost (annual). The do-nothing option only requires a repair/maintenance cost per failure.

The break rate of the pipe can be manually inputted by the estimated number of failures per year/100 km. Alternatively, a file can be imported that includes the year and number of breaks per 100 km, which can be gathered from risk modelling or data-driven pipe packages.

Figure 15 shows an example of the NPV analysis for the 3 options. A graph of NPV vs. the year after installation is also given. Simple results of the NPV after the years of analysis is also given at the bottom.



Pipe length : m 80

Years of analysis : yrs 100

Discount rate : % 5

Inflation rate : % 0

Option A: Replace

Cost of replace : $/m 1100

New replacement lifetime : yrs 50

Miscellaneous replace cost (annual) : $/y 0

Option B: Rehabilitate with Liner

Cost of liner : $/m 600

Liner lifetime : yrs 50

Miscellaneous liner cost (annual): $/y 0

Option C: Do Nothing

Repair/maintenance cost per failure : $ 2500

Select break rate: Manual Input | Import File

Est. number of failures per year / 100 km : 2000

NPV Criteria:
If NPV > 0 (NPV is +ve, Accept the Project)
If NPV < 0 (NPV is -ve, Reject the Project)
If NPV = 0 (Accept the Project, considering other non-tangible benefits)

Results of Net Present Value

Replace - NPV	Liner - NPV	Do Nothing - NPV
- $21344	$18656	- $79392

Figure 15. NPV analysis screen with parameters and graph

- **Length of pipe (L_p) -** The length of the pipeline or pipe length. Units are in m.
- **Years of analysis -** The amount of years to examine the NPV calculations for.
- **Discount rate (i) -** The interest rate used to determine the present value of the liner/replacement option. Units are in %.
- **Inflation rate (IN) -** The rate at which the prices increase over time, resulting in the lower purchasing value of money. Units are in %.
- **Cost of replace option (R_{cost}) -** The cost to replace the pipe using a traditional replacement method. Units are in $/m.
- **New replacement lifetime -** The expected life of a new replacement pipe asset, e.g. 50 years. Units are in years.

- **Miscellaneous replace cost (R_{mis}) -** Miscellaneous costs involved for a pipe replacement option, e.g. maintenance, failures, leak repairs, etc. Units are $/year.
- **Cost of the liner (L_{cost}) -** The initial cost to rehabilitate the pipe using a liner method such as CIPP or spray. Units are in $/m.
- **Liner lifetime -** The service life of the liner, e.g. 50 years. Calculated from long-term analysis using information from the lined pipe composite. Units are in years.
- **Miscellaneous liner cost (L_{mis}) -** Miscellaneous costs involved for a liner rehabilitation option, e.g. maintenance, failures, leak repairs, etc. Units are $/year.
- **Repair/maintenance cost per failure -** The average repair/maintenance cost per failure in the pipe using the do nothing approach. Units are in $.
- **Break information (break rate) -** Data analysis can be used by water utilities to import a file that includes the year and number of breaks per 100 km (can be gathered from risk modelling or data-driven pipe packages).
- **Estimated number of failures per year / 100 km -** The estimated number of failures per year/100 km. This value can be gathered from Water utilities data analysis. Units are in failures/y/100 km.

NOMENCLATURE

Liner Class (D, C, B, or A)

Liner type (CIPP or polymeric spray)

Reinforcement type (Glass or polymeric fibres) (for CIPP only)

A	Area of flow (mm^2)
c	Patch depth (mm)
c_{ACe}	External deterioration rate for AC pipes (mm/y)
c_{ACi}	Internal deterioration rate for AC pipes (mm/y)
c_d	Discharge coefficient
c_f	Fatigue constant for host pipe under cyclic surge pressure
c_l	Coefficient for strength reduction
c_{lc}	Coefficient for creep modulus reduction
c_{lf}	Coefficient for fatigue strength reduction
c_s	Intercept parameter for long-term corrosion of metallic pipes (mm)
C	Compression modulus (GPa)
C_{nothing}	Cost of do nothing option ($)
C_{HW}	Hazen Williams roughness coefficient
C_n	Total cash flow for each year ($)
$C_n(t)$	Nominal cash flow ($) at time t
$C_r(t)$	Real cash flow ($) at time t
CRF	Creep retention factor of the liner
d	Initial hole (defect) size (mm)
d_f	Future hole (defect) size (mm)
D	Pipe internal diameter (mm)
D_0	Pipe external diameter (mm)
D_L	Liner external diameter (mm)
D_{Li}	Liner internal diameter (mm)
D_M	Mean diameter of the host pipe (mm)
DN	Pipe nominal diameter (mm)
E_A	Short-term tensile or compressive modulus of the liner in the axial direction (GPa)
E_L	Short-term modulus of elasticity of the liner (GPa)
E_a	Young's modulus of the adhesive (GPa)
E_{fh}	Short-term flexural modulus of elasticity (hoop) of the liner (GPa)
E_{fhl}	Flexural creep modulus (hoop) of the liner (GPa)
E_{fa}	Short-term flexural modulus of elasticity (axial) of the liner (GPa)
E_{fal}	Flexural creep modulus (axial) of the liner (GPa)
$E_{l,dry}$	Dry creep modulus of the liner (GPa)
$E_{l,wet}$	Wet creep modulus of the liner (GPa)

E_p	Modulus of elasticity of host pipe material (GPa)
E_s	Soil modulus (MPa)
E_t	Short-term tensile modulus of elasticity of the liner (GPa)
E_{th}	Short-term tensile modulus of elasticity (hoop) of the liner (GPa)
E_{thl}	Tensile creep modulus (hoop) of the liner (GPa)
E_{ta}	Short-term tensile modulus of elasticity (axial) of the liner (GPa)
E_{tal}	Tensile creep modulus (axial) of the liner (GPa)
E_{tl}	Tensile creep modulus of the liner (GPa)
f	Friction coefficient of the interface of the host pipe and liner
g	Acceleration due to gravity (m/s^2)
h	Pressure head (m)
H	Burial depth (mm)
H_w	Groundwater depth (mm)
i	Discount rate (%)
IN	Inflation rate (%)
I_o	Initial investment ($)
k	Lateral earth pressure coefficient
k_1	Patch factor
k_2	Aspect ratio
K	Enhancement factor
K_{IC}	Fracture toughness of host pipe material (MPa m$^{1/2}$)
L	Installation length of the liner (m)
L_{cost}	Cost of the liner ($/m)
L_{mis}	Miscellaneous liner cost ($)
L_c	Critical crack length (mm)
L_p	Length of the pipe (m)
L_{ps}	Length of the pipe spool (m)
n_f	Cyclic surge factor
n_{PC}	Number of recurring cyclic surge pressure cycles per day
n_{TPC}	Total number of surge pressure cycles for the service life of pipe/lined pipe
N	Safety factor for host pipe
N_i	Factor of safety for liner imperfections
NPV	Net present value ($)
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	Host pipe ovality (%)
q_t	Total external pressure on pipes (MPa)
q_{tc}	Liner capacity for total external pressure (MPa)
Q	Leak rate (L/s)
r_s	Minimum corrosion rate (long-term) of metallic pipes (mm/y)
r_{sh}	Lateral corrosion rate for metallic pipes (mm/y)
r_{sv}	Radial corrosion rate for metallic pipes (mm/y)
R_{cost}	Cost of replace option ($/m)
R_h	Hydraulic radius (m)
R_{mis}	Miscellaneous replace cost ($)
R_W	Water buoyancy factor (unitless)
S	Slope of the energy grade line, or head loss per unit length of pipe (m/m)
t	Time (years)
t_h	Time (hours)
T	Pipe wall thickness allowing for uniform corrosion (mm)
T_L	Liner thickness (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_n	Pipe nominal wall thickness (mm)
u_g	Existing gap width of host pipe (mm)
u_{gp}	Gap formed due to axial movement or pulling force (mm)
V	Flow velocity (m/s)
W	Traffic load (kN)
W_s	Live load (MPa)
x_l	Coefficient for strength reduction
x_{lc}	Coefficient for creep modulus reduction
x_{lf}	Coefficient for fatigue strength reduction
y_f	Predicted year for failure of an AC pipe (mm)
α	Coefficient of thermal expansion (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)

θ	Rotation angle (°)
ν_L	Poisson's ratio of the liner
ν_p	Poisson's ratio of host pipe material
σ_A	Short-term tensile or compressive strength of the liner in the axial direction (GPa)
σ_{ad}	Adhesion strength of the liner to host pipe substrate (MPa)
σ_{fh}	Short-term flexural strength (hoop) of the liner (MPa)
σ_{fhl}	Long-term flexural strength (hoop) of the liner (MPa)
σ_{fa}	Short-term flexural strength (axial) of the liner (MPa)
σ_{fal}	Long-term flexural strength (axial) of the liner (MPa)
σ_{max}	Maximum stress in the liner (MPa)
σ_p	Tensile stress in the host pipe (for AC pipe) (MPa)
$\sigma_{t,AC}$	Ultimate tensile strength of AC (MPa)
σ_t	Tensile strength of the liner (MPa)
σ_t	Ultimate tensile strength of host pipe material (MPa)
σ_{th}	Short-term tensile strength (hoop) of the liner (MPa)
$\sigma_{thl,r}$	Tensile rupture strength (hoop) of the liner (MPa)
σ_{thl}	Long-term strength (hoop) of the liner and is the lesser value of either: the tensile rupture strength (hoop), $\sigma_{thl,r}$ (MPa) or fatigue strength (hoop), $\sigma_{thl.f}$ (MPa)
$\sigma_{thl.f}$	Fatigue strength (hoop) of the liner (MPa)
σ_{ta}	Short-term tensile strength (axial) of the liner (MPa)
$\sigma_{tal,r}$	Tensile rupture strength (axial) of the liner (MPa)
σ_y	Yield strength of steel (MPa)
τ	Transition period between short-term and long-term corrosion (y)
Φ	Soil friction angle (°)
ϕ_c	Wet creep reduction factor
ϕ_s	Wet strength reduction factor

DISCLAIMER

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

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

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

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

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

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