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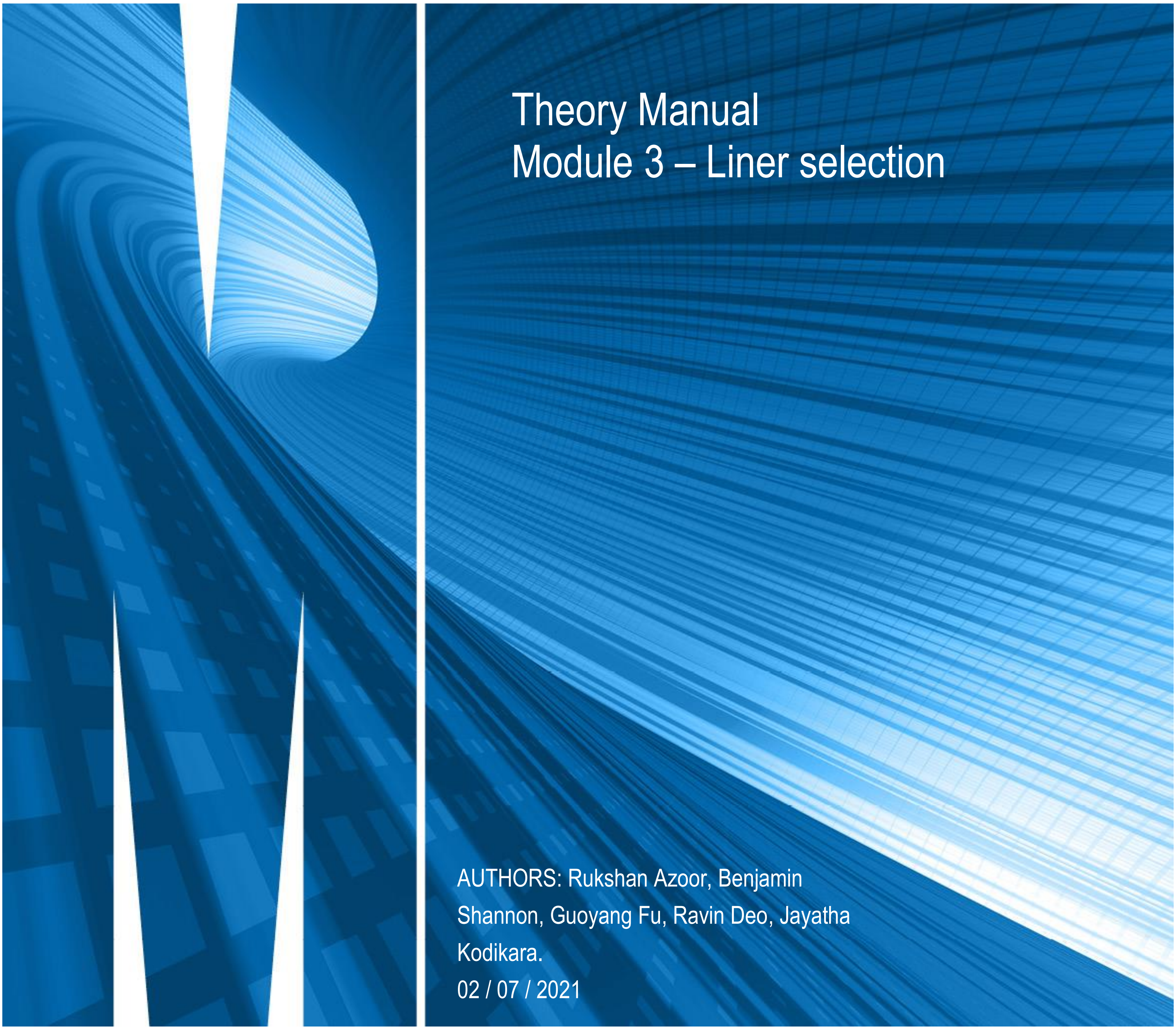

Theory Manual
Module 3 – Liner selection

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INTRODUCTION

Monash University were tasked to provide lining innovations to enhance market uptake, including a standard and code of practice of use for CIPP liners and spray liners for pressurised pipes in the CRC-project. This was conducted by undertaking literature reviews, field trials, laboratory testing, and numerical modelling. The research findings were implemented into a standard and code of practice for use in the Australian water industry. A decision tool known as the “Pipe Evaluation Platform” was developed to provide guidance to water utilities, applicators and liner manufacturers in the form of an online web-based platform.

The Pipe Evaluation Platform is split into four modules:

1. Pipe ranking
2. Pipe failure analysis
3. Liner selection
4. Lined pipe analysis

Each module provides tools to help the users to make decisions on pipe rehabilitation.

Module 3 – Liner Selection module

The following theory manual provides the theory behind the methods and processes used in the Liner Selection Module. The relevant equations used, assumptions made and parameter estimates adopted in the calculations are highlighted. The document is organised in a similar layout to that of the User manual and is designed to complement and detailed explanations to the methods presented therein.

1 LINER SELECTION MODULE

This document outlines the theory behind the methods and processes used in the liner selection module (Figure 1), which were outlined in the Liner Selection module User Manual.

The primary function of the liner selection module is to provide an initial estimate of a suitable lining type/method or any other renewal recommendation based on the available information about the pipeline/network. The calculations can be performed on an individual pipe segment or on a collection or a group of pipelines. In both approaches, the available information is used to establish the level of deterioration of the pipe and a respective **condition grade**. Recommendations are based directly on the condition grade.

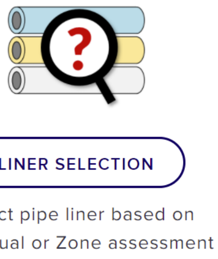

Figure 1. Liner selection module icon

2 CALCULATION PROCESS

The calculation process is organised into a three-step simple workflow to determine the condition grade of a pipeline before recommending a suitable liner. The three steps are, **pipe failure history**, **deterioration** and **leak rates**.

2.1 Step I-Failure history

In the failure history step, the past number of failures and the dominant failure type are used to estimate a condition grade related to the failure history

The number of past failures refers to an integer value corresponding to the number of times the particular pipe segment failed in the recent past (during a certain time frame such as 3 years). This time period can be specified according to user requirements during **utility data pre-processing**. The dominant failure type is the most common failure mode of these failure types. The available options for the failure type and their **severity rating** are provided in Table 1:

Table 1. Failure rating by severity for different failure types

Failure type	Severity rating	Explanation
Broken back	A	Ring crack
Piece blown off	B	Burst or leak
longitudinal crack	B	Burst or leak
Hole	B	Burst or leak
Leak	C	Leaks
Joint leak	C	Leaks
Tapping leak	C	Leaks
3rd party damage	D	Possible Leaks or none
None	D	Possible Leaks or none

Different utilities may use different terminologies for the failure type. This is addressed during utility data pre-processing by categorising different terminologies identified from utility data into the categories given in Table 1. The categories and classifications adopted for each different terminology is given in Table A1 in the Appendix.

If several types of failures had occurred in equal times for the given pipe segment, with no clear dominant failure type, it is recommended that the failure type with the most severe rating (Given in Table 1; with a rating A being the most severe and D being the least severe) be selected as the dominant failure type. In addition, a tolerable number of bursts can be set. This number, which is given as the number of bursts over the specific time period, is pre-selected as (3) 5. This number is used as a high-level check of the pipe segment to ensure that a warning is raised when the past number of failures over the specified time period exceeds this specific number.

The failure history of the pipeline that is input by the user is used to establish the condition grade based on the following criteria:

Table 2. Criteria for condition grade based on failure history

Condition grade	Failure history
1	No failures (severity A to D)
2	≤1 failure/km/year (severity C)
3	1-3 (severity C) or 0-1 (severity B or A[1]) failures/km/year
4	2-3 (severity B or A) failures/km/year
5	> 3 (severity A or B) failures/km/year

---

[1] *If broken backs (severity A) are dominant, reassessment is required before spray lining*

As given in the table above the condition grade depends on the numbers of past failures and the severity rating of the dominant mode of failure. The failure severity depends on the dominant failure type experienced by the pipe segment and is used as a guide to determine the most common type of stresses imparted on the pipe (Kodikara et al., 2012; Makar et al., 2000; Rajeev et al., 2013). As evidenced by research, most small diameter pipes fail in circumferential cracks due to bending loads. From a lining perspective, this failure mode is the most critical followed by other modes such as piece blown off and longitudinal crack. This is reflected in the criteria summarised in Table 1.

The final condition grade will determine the final liner recommendation. Prior to this, condition grades are determined from the other two steps as described in the following sections.

2.2 Step II - Deterioration

The deterioration component depends on the type of pipe material and the external environment. The corrosion deterioration for metallic pipes, including cast iron and mild steel, will depend on the external environment and the time dependent ferrous corrosion rates in soil. The deterioration rate for AC pipes will depend primarily on the material characteristics.

2.2.1 Metallic pipe deterioration

Metallic pipe corrosion can be modelled using the power law equation (Rajani et al., 2000) given in Equation (1) is used for the corrosion patch depth estimation.

$$c = r_s(t - t_0) + c_s\left(1 - exp\left(\frac{-(t - t_0)}{\tau}\right)\right) \tag{1}$$

where c is the corrosion patch depth (mm), r_s is the minimum corrosion rate (long-term) of metallic pipes (mm/y), c_s is the intercept parameter for long-term corrosion of metallic pipes (mm) and τ is the transition period between short-term and long-term corrosion (y). Time in years is indicated by t and t_0 is termed the holiday period, which is the time till coating damage occurs. In the liner selection module calculations outlined in this document, the holiday period is assumed to be zero. i.e., t_0= 0. Note that t_0 being zero, the corrosion curve begins at the origin. With this assumption, the power law model for corrosion is given in Figure 2.

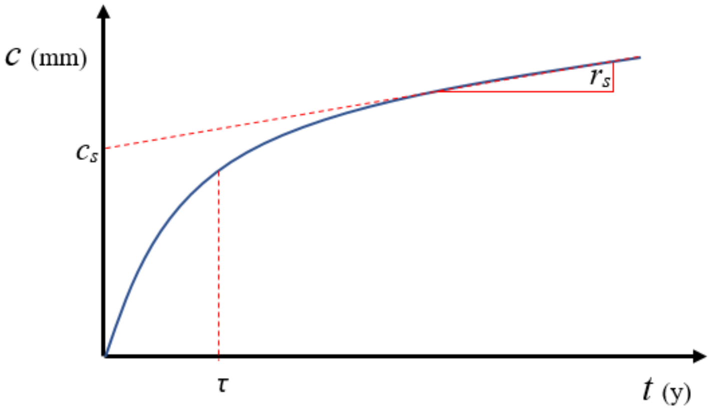

Figure 2. The power law model for metallic corrosion

The values of the parameters will determine the overall corrosion behaviour and intensity. Based on experimental/field observations and analysis (Jiang et al., 2017), the following parameter values are assigned to various categorical corrosion rates Table 3.

Table 3. Parameter values for different corrosivity levels

Soil corrosivity category	r_s (mm/y)	c_s (mm)	τ (y)
Very low	0.0042	1.95	17.24
low	0.021	9.75	17.24
Moderate	0.0252	11.7	17.24
High	0.0294	13.65	17.24
Very high	0.0336	15.6	17.24

The power model curves corresponding to the above categories are given in Figure 3. It can be seen that apart from the very low category, the patch depths after 50 years exceed 10 mm for all the categories.

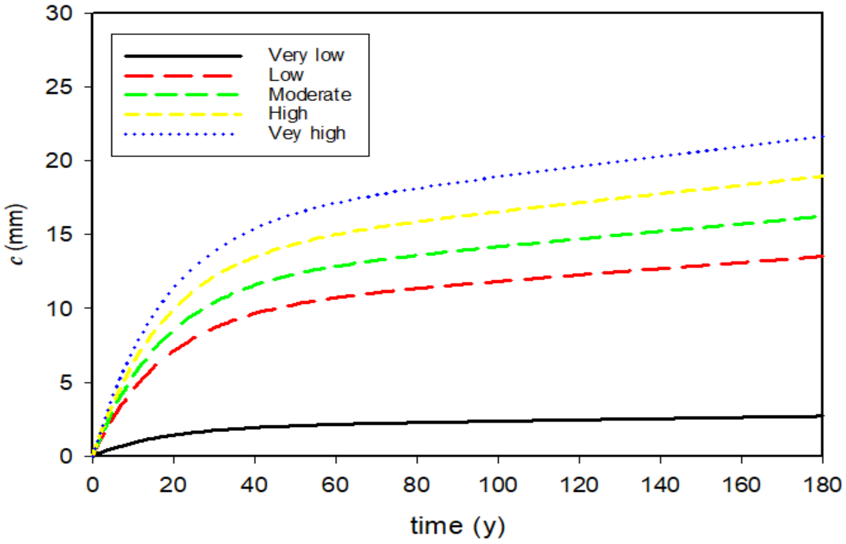

Figure 3. Power law model curves corresponding to the corrosivity categories

The above categories are assigned based on soil types. It is generally accepted that the soil texture, in particular the clay content, is correlated with the corrosivity, with sand being the least corrosive and clay the highest (Azoor et al., 2019; Deo et al., 2014). Therefore, the categories are assigned to different soil types in the global soil table as given in Table 4.

Table 4. Corrosivity category assignment for different soil types

Soil type	Likely Corrosivity
Sand	Very low
Loamy sand	Very low
Sandy loam	Very low
Fine sandy loam	Low
Loam	Low
Silty loam	Moderate
Sandy clay loam	Moderate
Fine sandy clay loam	High
Clay loam	High
Silty clay loam	High
Sandy clay	Very high
Light clay	Very high
Silty clay	Very high
Medium clay	Very high
Heavy clay	Very high

Once the corrosivities are established, the probable defect sizes in the host pipe need to be calculated. Corrosion patches typically assume a semi-ellipsoidal shape (Deo et al., 2019). The semi-ellipsoid is defined using the parameters *a, b,* and *c* denoting the patch half-length (mm), patch half-width (mm) and the patch depth (mm) respectively. The ratio between *a* and *b* is termed the **patch factor** and is assumed to be constant for all patches and is a global variable with a default value of 5. This means that the maximum extent of the patch, in terms of surface area can be expressed using Eq. 2

$$A = \pi \frac{a^2}{k_1} \tag{2}$$

where the patch factor, $k_1 = a/b = 5$

For ease of visualisation, the 2-D section along the longitudinal axis of the semi-ellipsoid is shown in Figure 4. It is assumed here that the patches propagate while maintaining the same proportions as shown in Figure 4.

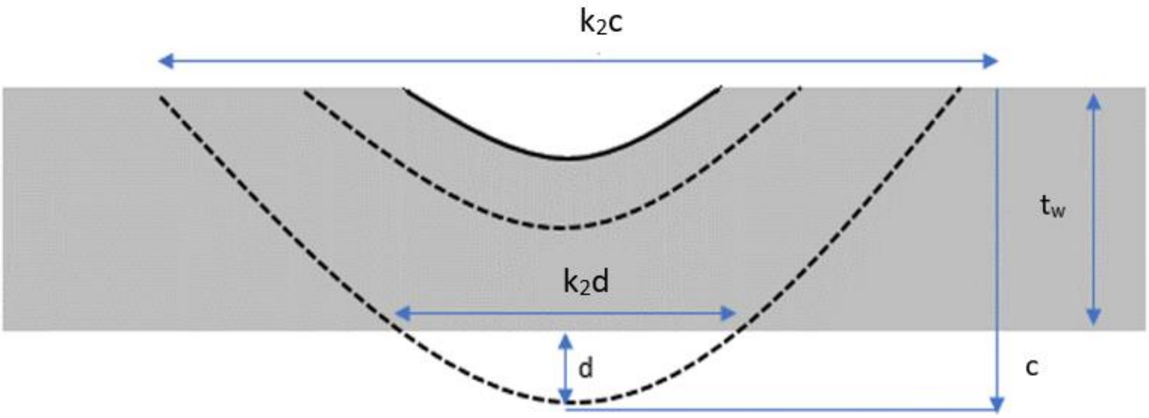

Figure 4. Schematic showing corrosion patch propagation and defect size calculation

Based on observations on real corrosion patches, it has been estimated that the lateral extent of the patch approximately is 10 times the maximum depth, c. This factor is termed the **aspect ratio** (Deo et al., 2019). Based on observations of failed pipes, the aspect ratio is assumed to be 10 ($k_2 = 2a/c = 10$) and is also assumed to be a constant. The factors k_1 and k_2 can be changed in system variables.

Once the maximum patch depth (c) is found using Equation (1), the surface area of the patch (A) (mm^2) can be found using Equation (3):

$$A = \frac{\pi}{4}\frac{k_2^2}{k_1}c^2 \tag{3}$$

If corrosion leads to a through-wall defect and if the nominal pipe wall thickness (T_n) (mm) is known, the surface area of the through-wall hole (at the internal surface, as indicated in Figure 4) can be thus found using Equation (4):

$$A = \frac{\pi}{4}\frac{k_2^2}{k_1}(c - T_n)^2 \tag{4}$$

The surface area of the through-wall hole in the internal surface is used because, a potential liner would need to bridge this hole. The pipe wall thickness (T_n) can be found using information on installation year, pipe diameter and pressure head, based on cohort analysis. (See the document: TM M2 Part 1 – Pipe cohorts for a description of cohort analysis methods used for this purpose).

Once the internal surface area of a through-wall hole is found, a condition grade is assigned based on the severity of the defect. If the pipe wall is not fully penetrated, the condition grade is assigned based on percentage loss in wall thickness as indicated by the patch depth c (See Table 5).

2.2.2 AC Pipe deterioration

AC pipes typically deteriorate due to lime leaching that results in softening of the internal and external surface of the pipe. Sulphate attack also can deteriorate an AC pipe in similar fashion. The softening of the surfaces gives drastic reduction in tensile strength (close to zero) of the deteriorated wall. The deterioration has been approximated as a relatively constant rate (Water New Zealand, 2017) from time of installation of the pipe.

A constant rate of deterioration as that used by Water New Zealand was adopted. This fixed rate of deterioration will be based on the combined deterioration rate (internal deterioration rate + external deterioration rate) and the years the deterioration has occurred over. The default values for the external and internal corrosion rates are be set to the values from Water New Zealand, which are 0.123 mm/y and 0.1114 mm/y respectively. The reason for using wall thickness deterioration in the model is due to the fact wall thickness measurements are easier than testing for tensile strength. The approximate initial tensile strength and wall thickness are known from cohorts (See the document: TM M2 Part 1 – Pipe cohorts).

$$T = T_n - c_{AC}y \tag{5}$$

where T is the current approximated pipe thickness (mm), T_n is the initial nominal wall thickness (mm), c_{AC} is the AC deterioration rate (mm/year), and y is the age of the host pipe.

$$c_{AC} = c_{ACi} + c_{ACe} \tag{6}$$

where c_{ACi} is the internal deterioration rate for AC pipes (mm/y) and C_{ACe} is the external deterioration rate for AC pipes (mm/y).

The pipe remaining service life is predicted to end when the remaining wall thickness cannot withstand the internal pressure (P) as shown in Equation (7). This remaining wall thickness at failure (mm) is termed T_f as shown in Equation (7).

$$P = \frac{2\sigma_{t,AC}(T_f)}{DN} \tag{7}$$

where $\sigma_{t,AC}$ is the tensile strength of asbestos cement (MPa), D is the pipe internal diameter and N is the host pipe safety factor. T_f is obtained by subtracting the product of time to failure y_f and total deterioration rate by the initial thickness. Hence, re-arranging Equation (7):

$$T_f = T_n - c_{AC}y_f = \frac{PDN}{2\sigma_{t,AC}} \tag{8}$$

where y_f is the predicted year for failure of an AC pipe (y), N is the safety factor for host pipe. Therefore, the remaining life of the AC pipe can be found using Equation (9):

$$y_f = \frac{\left(T_n - \frac{PDN}{2\sigma_{t,AC}}\right)}{c_{AC}} \tag{9}$$

A factor of safety, $N = 1$, can be set if conservative estimates are not required.

The condition grade for the AC pipe is determined based on the years remaining till failure calculated from Equation (9).

2.2.3 Condition grade criteria

The condition grade for both metallic pipes and AC pipes are summarised in Table 5. For cast iron pipes, the condition grade is based on the estimated defect size based on soil corrosivity. If a through-wall defect is present, the condition grade depends on the calculated patch size. If not, the maximum depth of the patch as related to the wall thickness is used. For AC pipes, the remaining life calculated based on the internal and external deterioration rates pipe age, diameter and pressure class.

Table 5. Condition grade calculation criteria used in the deterioration step for metallic and AC pipes

Condition grade	**Cast iron** **Deterioration**	**Asbestos cement** **Remaining life in years**
1	Patch depth <50% wall thickness	50 or more
2	Patch depth between 50-80% wall thickness	20-50
3	Patch depth >80% wall thickness Defect size <1000 mm^2 if present	10-20
4	Defect size 1000-2000 mm^2	5-10
5	Defect size >2000 mm^2	0-5

2.3 Step III - Leak rates

If leak rates of a pipeline are measured, and if the pressure is known, the approximate defect size can be calculated from orifice equation (Kabaasha et al., 2018; van Zyl et al., 2017). It should be noted that the measured leak may occur from multiple small defects. However, as a conservative estimate, only the effective size of a single defect is estimated.

For the calculation, the maximum measured leak rate for the pipe segment along with the operational pressure head (h) in m. Based on these inputs, the orifice equation (van Zyl et al., 2017) (Equation (10)) is used to estimate the defect area:

$$A = \frac{1000 \cdot Q}{c_d\sqrt{2gh}} \tag{10}$$

where A is the defect area in mm^2, Q is the leak rate (Ls^{-1}), g is the acceleration due to gravity (ms^{-2}), h is the pressure head (m), and c_d is a non-dimensional constant termed the discharge coefficient, which set to 0.61 by default (Schwaller and van Zyl, 2015), but may be modified by the user.

The calculated defect areas are used to determine a condition grade similar to previous steps. However, as the presence of a leak indicates that the host pipe is already compromised, and that the pipe cannot be in good condition, only the worst grades of 4 or 5 are assigned based on leak rates. Thus, the area calculated from the orifice equation (van Zyl et al., 2017) is compared against a critical defect area of 1000 mm^2 to assign the condition grade as given below in Table 6.

Table 6. Condition grade calculation from leak rates

Condition grade	**Defect area calculated from Leak rate**
4	< 1000 mm^2
5	> 1000 mm^2

3 SUMMARY OF INPUTS, OUTPUTS AND WORKFLOW

The three steps described above in the order, *failure history*, *deterioration* and *leak rates* form the overall workflow of the liner selection module. It is noted that all the modules are optional and that only one method is required to estimate the condition grade of the pipe leading to a liner recommendation. Any of the three steps can be skipped as required. In the case where inputs to multiple steps are satisfied, the maximum condition grade resulting calculated from the multiple steps will be used for the recommendation.

A summary of the inputs used for the three modules are given in Table 7.

Table 7. Summary of inputs for the three modules

Calculation Step	Simple input	Advanced input
Failure history	• Number of past failures • Dominant failure type	• Tolerable number of interruptions (Default 5)
Deterioration	• Pipe installation year • Pipe material (Metallic or AC) • Pipe diameter (mm) • Pressure head (m) (operational pressure) • Soil type or corrosivity	• Deterioration model parameters (estimated based on simple inputs) • Pipe nominal thickness (estimated based on simple inputs)
Leak rates	• Leak rate (litres/s) • Pressure head (m)	• Discharge coefficient • (Default 0.61)

Based on the final condition grade calculated (maximum condition grade if more than one are found), the liner recommendation is provided as given in Table 8.

Table 8. Final liner recommendation criteria

Condition grade	Recommendation options
1	1) Do nothing
2	1) Do nothing 2) Spray or CIPP (Class C to B)
3	1) Do nothing 2) Spray or CIPP (Class C to B) 3) CIPP (Class A)
4	1) CIPP (Class A) 2) Spray or CIPP (Class C to B) [2] 3) Replace
5	1) Replace 2) CIPP (Class A)

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[2] If broken backs (severity A) are dominant, reassessment is required before spray lining

3.1 Flowchart of calculations in the liner selection module

Figure 5 shows a flowchart summarising the calculations and processes detailed above. Note that when more than one step is selected the maximum condition grade is used for the liner recommendation.

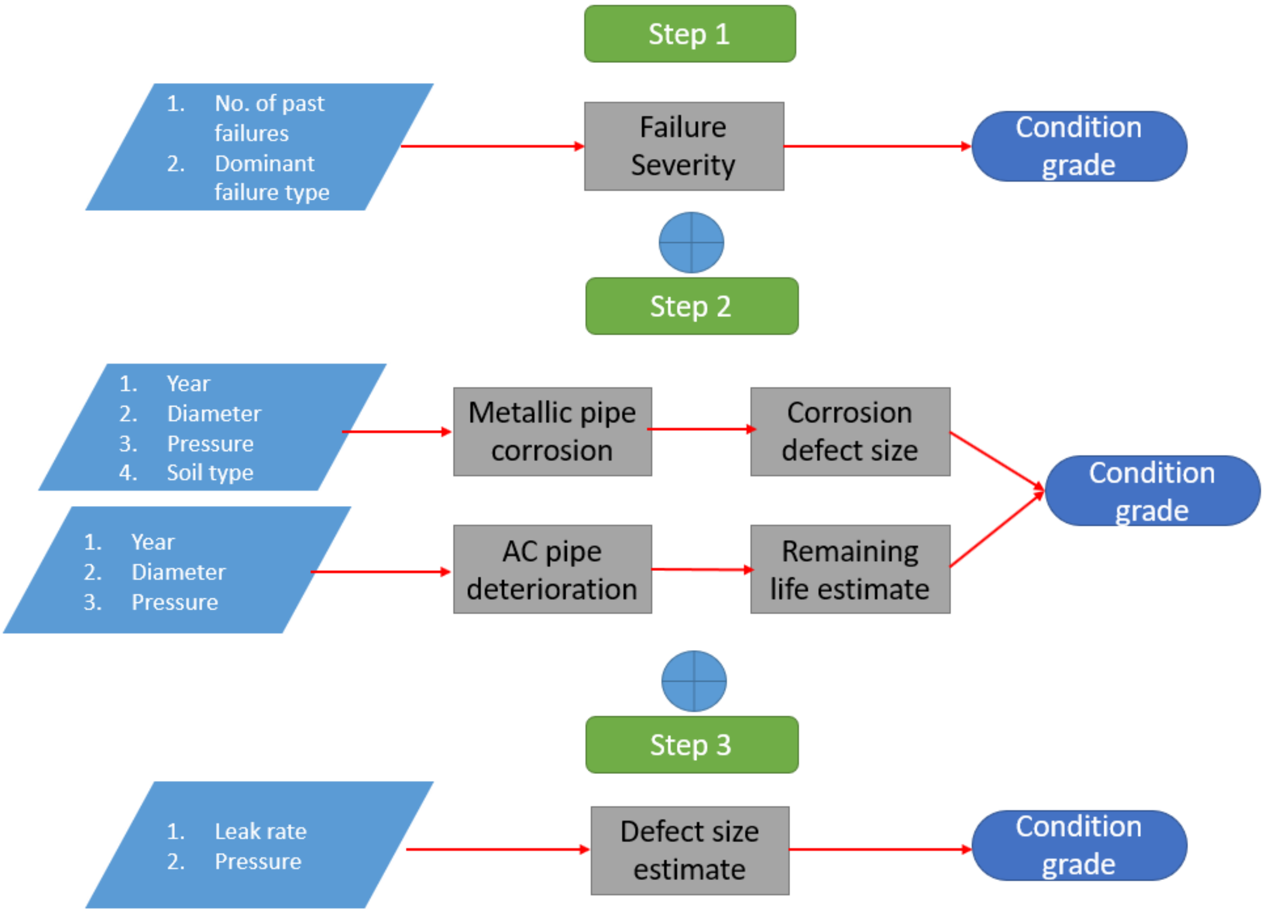

Figure 5. Flowchart summarising processes in the liner selection module

3.2 Approximate defect size or remaining wall thickness characterisation

For further assessment of liner applicability, the defect sizes or remining wall thickness corresponding to each method are also estimated. For the metallic pipes in the deterioration and leak rates step, the defect areas are found using Equation (4) and Equation (10) respectively. For AC pipes, the remaining wall thickness is estimated using Equation (5).

For consistency, the defect area was also estimated for the failure history step. This was achieved by examining the defect areas in pipelines of various diameters that failed in a variety of failure modes. Based on this information, the defect area (A) in mm was related to pipe internal diameter (D) in mm using the following relationship:

$$A = p_1 e^{p_2 D} \tag{11}$$

where p_1 and p_2 are constants that depend on the failure severity. The values of p_1 and p_2 assigned to each failure severity category are given in Table 9:

Table 9: Defect area calculation constants based on failure severity

Severity rating of defect	***p₁***	***p₂***
A	101.90	0.0092
B	28.813	0.0121
C	8.412	0.0096
D	4.00	0.0090

Once the defect area was estimated based on any of the following methods, the dimensions corresponding to a circular defect, elliptical patch and gap width of host pipe (assumed broken back failure) were calculated using Equations (12), (13) and (14):

Major axis length of elliptical patch (a) in mm:

$$a = \sqrt{\frac{Ak_1}{\pi}} \tag{12}$$

Diameter of circular patch (d) in mm:

$$d = \sqrt{\frac{4A}{\pi}} \tag{13}$$

Gap width of host pipe (assumed broken back failure) (u_g) in mm:

$$u_g = \frac{A}{\pi D} \tag{14}$$

These calculated dimensions are accessible via advanced results and are expected to be useful in the further assessment of liner applicability in relation to hole spanning and gap spanning capabilities, Detailed analysis of such hole and gap spanning together with liner and hole host pipe analysis can be performed in the Lined Pipe Analysis module. (See the theory manual for the Lined Pipe Analysis module for details, “TM M4 Part 2 – Lined pipe analysis”).

NOMENCLATURE

Condition grade – A number from 1 to 5 indicating the severity of the deterioration of the pipeline. 5 being the most severely deteriorated and 1 being a pipe in pristine condition.

Step I pipe failure history – The calculation step where the past number of failures over a given time period and the domain failure type experienced during that period are used to estimate a condition grade for a pipe segment

Step II deterioration – The calculation step where the pipe material, age and soil conditions are used to estimate the level of deterioration based on available deterioration models, to finally estimate a condition grade for the pipe segment

Step III leak rates – The calculation step where measured leak rates are used to estimate the defect size based on the orifice equation to finally estimate the condition grade of the pipe segment

Severity rating – A rating assigned to a failure type ranging from A – D with A being the most severe and D the least severe.

Utility data pre-processing (see user manual for more details) – A method to format raw data from utilities to the input format of the pipe evaluation platform. Processing can be done through programming scripts developed by Monash University or using the pivot table functionality in MS Excel.

$2a$	Patch length (mm)
$2b$	Patch width (mm)
A	Area of flow (mm^2)
c	Patch depth (mm)
c_{ACi}	Internal deterioration rate for AC pipes (mm/y)
c_{ACe}	External deterioration rate for AC pipes (mm/y)
c_d	Discharge coefficient
c_s	Intercept parameter for long-term corrosion of metallic pipes (mm)
d	Initial hole (defect) size (mm)
D	Pipe internal diameter (mm)
g	Acceleration due to gravity (m/s^2)
k_1	Patch factor
k_2	Aspect ratio
r_s	Minimum corrosion rate (long-term) of metallic pipes (mm/y)
h	Pressure head (m)
N	Safety factor for host pipe
P	Operating pressure (MPa)
Q	Leak rate (L/s)
r_{sv}	Radial corrosion rate for metallic pipes (mm/y)
r_{sh}	Lateral extension rate for metallic pipes (mm/y)
T_f	AC pipe remaining wall thickness at failure (mm)
T_n	Pipe nominal wall thickness (mm)
u_g	Existing gap width of host pipe (mm)
y_f	Predicted year for failure of an AC pipe (mm)
$\sigma_{t,AC}$	Ultimate tensile strength of AC (MPa)

τ Transition period between short-term and long-term corrosion (y)

DISCLAIMER

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

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

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

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

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

CONCLUSIONS

This document outlined the theory behind the methods and calculations used in the Liner Selection Module. The content was presented in the same format as that of the user manual to aid the user follow the process with the relevant background for each method. References were provided previously developed methods or parameter estimations were adopted.

APPENDIX

Table A1 – Classifications adopted for different utility terminologies

Broken back	**Piece blown off**	**Longitudinal crack**	**Hole**	**Leak**	**Joint failure**	**Tapping failure**	**Fitting failure**	**Other**
B.BACK	BLOWN JOINT	LONG FRACTURE	PINHOLE	LEAKING PIPE	damaged flange joint	FRACTURE AT FERRULE	FAULTY FITTING	Abandoned ferrule
B/BACK	BLOWN OUT	LONGITUDINAL FRACTURE	DRILL HOLE	LEAK ON A ABANDONED MAIN	damaged rubber ring joint	FAULTY FERRULE BEND	FAULTY GIBAULT	CORRODED ON BOTTOM
BROKEN	PIECE BLOWN OUT	LONGITUDINAL FRAC	HOLE IN PIPE	leaking	perforated weld joint	FAULTY FERRULE BAND	FAULTY GIBAULTS	CORRODED
circumferential break	Blown section	LONGITUDINAL FRACT	PINHOLES	SWEAT PATCH	LEAD JOINT	TAPPING FAILURE	FAULTY GIBBO	LOOSE BOLTS
CIRCUM FAIL	blown	LONGITUDINAL FRACTUR	SMALL HOLE IN MAIN	WEEPING	rubber ring joint	FERRULE OUT	FAULTY REPAIR CLAMP	FERRULE NOT IN USE
CIRCUM FAILURE		longitudinal split	PERFORATION		damaged lead joint	OLD FERRULE OUT	FAULTY TAPPIN BAND	FIRE PLUG
circumferential fracture		BURST	perforated		LEAKING JOINT	Tapping leak	GIBAULT RUBBER BLEW OUT	PULLED FERRULE
GROUND MOVEMENT		FRACTURED			LEAKING LEAD JOINT		TAPPING SADDLE FAILURE	HYD STACK
		split			Joint leak		TAPPING BAND FAILURE	HYDRANT FAULT
		failed					TAPPING SADDLE	LOCATE AND RAISE
							tapping saddle fracture	MINOR
							Fitting	NEW SCOUR PIPE

Broken back	Piece blown off	Longitudinal crack	Hole	Leak	Joint failure	Tapping failure	Fitting failure	Other
							Tapping Bands	OLD AGE
							LOOSE CLAMP	OTHERS
							LEAK AIR VALVE	POLY MAIN
							LEAKING CLAMP	SOFT PIONTS IN PIPE
							LEAKING FITTING	UNKNOWN
							LEAKING REPAIR CLAMP	UNSPECIFIED
							leaking maintaps	VALVE OPERATION
							leaking valves	faulty
							POP RIVETS LEAKING AS WELL	damaged
							leaking other fitting	3rd party damage
								None

REFERENCES

Azoor, R.M., Deo, R.N., Birbilis, N., Kodikara, J., 2019. On the optimum soil moisture for underground corrosion in different soil types. Corros. Sci. 159, 108116. https://doi.org/10.1016/j.corsci.2019.108116

Deo, R.N., Birbilis, N., Cull, J.P., 2014. Measurement of corrosion in soil using the galvanostatic pulse technique. Corros. Sci. 80, 339–349. https://doi.org/10.1016/j.corsci.2013.11.058

Deo, R.N., Rathnayaka, S., Zhang, C., Fu, G.Y., Shannon, B., Wong, L., Kodikara, J.K., 2019. Characterization of corrosion morphologies from deteriorated underground cast iron water pipes. Mater. Corros. 1–15. https://doi.org/10.1002/maco.201910906

Jiang, R., Shannon, B., Deo, R.N., Rathnayaka, S., Hutchinson, R., Zhao, X., Kodikara, J., 2017. Classification of major cohorts of Australian pressurised cast iron water mains for pipe renewal. Australas. J. Water Resour. 1583, 1–12. https://doi.org/10.1080/13241583.2017.1402979

Kabaasha, A.M., Piller, O., van Zyl, J.E., 2018. Incorporating the Modified Orifice Equation into Pipe Network Solvers for More Realistic Leakage Modeling. J. Hydraul. Eng. 144, 04017064. https://doi.org/10.1061/(asce)hy.1943-7900.0001410

Kodikara, J., Rajeev, P., Robert, D., Zeman, P., 2012. Critical review of historical information on large diameter pipe failure. ACAPFP Proj. Act. 1 Report No. CPP-A1-R1.

Makar, J.M., Desnoyers, R., McDonald, S.E., 2000. Failure Modes and Mechanisms in Gray Cast Iron Pipes. NRC Publ. Arch. 1–11.

Rajani, B., Makar, J., McDonald, S., Zhan, C., Kuraoka, S., Jen, C.K., Veins, M., 2000. Investigation of Grey Cast Iron Water Mains to Develop a Methodology for Estimating Service Life. AWWA Research Foundation and American Water Works Association.

Rajeev, P., Kodikara, J., Robert, D., Zeman, P., Rajani, B., 2013. Factors Contributing To Large Diameter Water Pipe Failure As Evident From Failure. 9–14.

Schwaller, J., van Zyl, J.E., 2015. Modeling the Pressure-Leakage Response of Water Distribution Systems Based on Individual Leak Behavior. J. Hydraul. Eng. 141, 04014089. https://doi.org/10.1061/(asce)hy.1943-7900.0000984

TM M2 Part 1 – Pipe cohorts, Theory manual for the Pipe Evaluation Platform, Monash University 2021

van Zyl, J.E., Lambert, A.O., Collins, R., 2017. Realistic Modeling of Leakage and Intrusion Flows through Leak Openings in Pipes. J. Hydraul. Eng. 143, 04017030. https://doi.org/10.1061/(asce)hy.1943-7900.0001346

Water New Zealand, 2017. National Asbestos Cement Pressure Pipe Manual Volume 2.