Australian Government
Department of Industry, Innovation and Science

Business Cooperative Research Centres Program

MONASH University Civil Engineering

Theory Manual
Module 2 – Pipe failure analysis
Part 1 – Pipe and soil cohorts

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06 / 08 / 2021

MONASH PIPE
EVALUATION PLATFORM

MONASH University

QUALITY INFORMATION

Document: Theory Manual, Module 2 – Pipe failure analysis, Pipe and soil cohorts

Edition date: 06-08-2021

Edition number: 1.2

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Reviewed by: Rukshan Azoor, Guoyang Fu

Revision history

Revision	Revision date	Details	Revised by
1.1	05-07-21	Updated document	Ben Shannon
1.2	06-08-21	Added soil cohorts, and basic MS and DICL cohort	Ben Shannon

CONTENTS

ACKNOWLEDGEMENTS

The Australian Government, through the Cooperative Research Centre, provided funding for the Smart Linings for Pipe and Infrastructure Project that produced this report. The CRC Program supports industry-led collaborations between industry, researchers and the community.

Australian Government
Department of Industry, Innovation and Science

Business Cooperative Research Centres Program

The project was led by the Water Services Association of Australia (WSAA) and included the following project partners, all of whom contributed expertise, labour, funding, products or trial sites to assist in the delivery of this project.

Abergeldie Watertech

BASF Australia

Bisley & Company

Calucem GmbH

Central Highlands Water

City West Water Corporation

Coliban Region Water Corporation

Downer

GeoTree Solutions

Hunter Water Corporation

Hychem International

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Sydney Water Corporation

The Australasian Society for Trenchless Technology (ASTT)

The Water Research Foundation

UK Water Industry Research Ltd (UKWIR)

Unitywater

University of Sydney

University of Technology Sydney

Urban Utilities

Ventia

Water Corporation

Wilsons Pipe Solutions

Yarra Valley Water

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 "Monash 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 Monash 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 2 Part 1 examines the cohort property values of host pipes used throughout the Monash Pipe Evaluation Platform (Pipe failure Analysis module). The information on each of the pipe types examined in this are used to gather material properties, dimension of the host pipe. The following document examines the theory used to determine host pipe properties for the Pipe cohorts.

1 PIPE COHORTS

Water utilities collect key pipe data on water assets such as length, depth, diameter, material and age. This data is kept in an asset management database with records of pipe performance and together can be used to create models to assist in maximizing the efficiency of the water system. As time progresses, data recording gets progressively better, easier and cheaper, this provides a great opportunity for utilities to inexpensively improve their asset data bases, resulting in better models, better decisions and greater efficiency.

The idea of pipe cohorts is to break down pipe information based on types of pipes, class, pipe diameters, wall thickness and material properties. The information gathered from cohorts can be directly inputted into the Monash Pipe Evaluation Platform, as an automated method to gather data needed for decisions.

A total of four pipe types were examined for use: cast iron (CI), asbestos cement (AC), ductile iron (DI) and mild steel (MS). Other types can be added with further research and funding.

1.1 Host pipe diameter and thickness

Wall thickness is a vital parameter used in the design of pressure pipes, along with loading (internal and external) and pipe diameter. By recording wall thickness, we can greatly improve model accuracy (internal pressure can be monitored and diameter is typically recorded). Barlow's formula (below) determines the internal pressure that a pipe can withstand.

$$P = \frac{2\sigma_t T}{D} \qquad (1)$$

where P = internal pressure, σ_t = tensile (hoop) strength of the pipe, T = wall thickness of the pipe and DD = diameter of the pipe

By using Barlow's equation (1), we can see that a small change in thickness will make a significant difference to the pressure holding capacity, if thickness is doubled, the pressure capacity is also doubled. The same can be said for both tensile strength and diameter. Therefore, it is imperative to find these three properties.

Classes of pipes typically have a pressure rating, and a subsequent wall thickness, suitable to withstand a nominated pressure plus a factor of safety. Water engineers use that pressure rating to select what pipes to install.

When creating models of the water system, knowing the wall thickness, or pressure rating, is critical to determine a pipe's likely time of failure. When this information is not available it must be estimated based on data that is available. Making such estimates reduces model accuracy, however if based on the cohort analysis give the best possible data without directly examining and testing the host pipe.

1.2 Cohort data

When estimating wall thickness typically cohort data must be used. Wall thickness data is usually derived from pressure class. For example, cast iron (CI) pipes have 3 to 4 classes (A to D, where D has the largest wall thickness), depending on the year and standard used (British Standards 1938, Australian Iron and Steel 1941, Nicholas and Moore 2009, Shannon et al. 2016, Jiang et al. 2017). Asbestos cement (AC) pipes have six pressure classes (A to F, where F has the largest wall thickness) (AS 1171 1975). Ductile iron was typically made with two different pressure classes (PN ratings or K ratings) (AS 2280 1979, AS 2280 2004). Mild steel has various strength classes, and usually has varying wall thickness depending on the diameter of the pipe (AS A125 1963, AS 1579 2001). However, standards change over time as do manufacturing processes resulting in variation in wall thickness values. Further details on the cohort method for each pipe type can be found in the subsequent subsections.

Cohort data is also used for other of properties, such as tensile strength, Elastic modulus, Poisson's ratio, Fracture toughness, inner and outer coating, burial material, etc[1]. While useful, each approximation reduces the accuracy of the model. However, if minimal information is known about the pipe, the cohort values give a good approximation for the input parameters.

To further complicate matters, as material manufacturing processes improved over time, so did the strength of materials. AC pipes and cast-iron pipes both increased tensile strength values as manufacturing processes improved. These changes in material values are incorporated into the cohort data in deterioration models.

1.3 How is wall thickness used for deterioration?

Pipes deteriorate over time due to corrosion and/or fatigue (metallic pipes) and/or lime leaching (AC). Uniform corrosion for metal pipes and lime leaching for AC pipe effectively reduce the wall thickness of the host pipe. Corrosion can also induce localised corrosion pits (cast iron and mild steel), which can cause stress concentrations in the pipe. For further information on deterioration please see "TM M3 - Liner selection document".

Except for critical pipes, it is generally not economical for utilities to undertake condition assessment on pipes. Without a condition assessment, original pipe parameters (gathered from cohort data) are used with a deterioration model to predict the current pipe condition and remaining life. If the current pipe condition is known, it can be used to calibrate the deterioration prediction model, e.g. phenolphthalein wall thickness test for AC or wall thickness scans for CI pipes. However, if no condition assessment is conducted, cohort values can provide a good approximation on the pipe properties and wall thickness.

1.4 Cohorts for host pipe

The following subsections give information on how the cohort values for cast iron, Asbestos cement, ductile iron and mild steel are gathered.

1.4.1 Cast iron pipe cohort

Buried ferrous water mains are subject to complex environmental conditions, which can cause deterioration over the water mains service lifetime. Significant variation of the cast iron pipe physical properties exist as a result of the long span of manufacture and environmental changes (Rajani et al. 2000, Rajani et al. 2011). Cast iron pipe properties are important to determine remaining residual pipe strength (Fahimi et al. 2016), numerical modelling of tests (Ji et al. 2015) and pipe failure prediction (Shannon et al. 2016). Significant testing of cast iron pipes in North America and the UK have been published (Conlin and Baker 1991, Rajani et al. 2000, Seica and Packer 2004, Makar and McDonald 2007, Belmonte et al. 2008), material properties from Australian cast iron pipes (Shannon et al. 2016, Jiang et al. 2017).

Many Water utility data records have missing information about pipes such as: manufacturing type, wall thickness, failure data, repair data and correct location. This makes single value cohorts difficult to apply. As casting techniques improved, so did the strength of the cast iron pipe. However, this came at a cost with the

[1] Note inner coating (apart from CML), outer coating and burial material are not included in the current Pipe Evaluation Platform.

coinciding reduction in wall thickness. The reduction in wall thickness meant a reduction in the time for corrosion to penetrate the cast iron and form a through-wall pit.

For CI pipes cohorts, the relevant standard was examined to determine further pipe information (Table 1). Five standards were used. Information can be gathered from the standards such as wall thickness, pipe diameters, tensile strength and class. Any cast iron pipe installed before 1917 will be assigned cohort values based on BS 78 (1917). Data will need to be modified by the user if known to vary from the standards provided. Material properties of cast iron were based on standards and testing conducted by Monash University (Shannon et al. 2016, Jiang et al. 2017).

Australian cast iron pipes were typically designed to the same sizes used in British Standards. The pipe outer diameter was kept consistent with that found all the way up to ductile iron pipes for ease of line maintenance. As the outer diameter was kept consistent, the inner diameter varied with changing class/wall thickness (larger class had larger wall thickness and lower internal diameter).

Table 1. Installation year and corresponding standard.

Installation period	Standards
0[2]	BS 78 (1917)
1938	BS 78 (1938)
1953	AIS (1953)
1965	AS A145 (1965), AS A145 (1970)[3]
1975	AS 1723 (1975), AS 1724 (1975)

For CI pipes there are typically 4 different pressure classes (Class A to D[4], with A being the thinner wall size), however, in the field we would only see pipes in Class B or above (Class A were used for gas pipelines only and would be too low for typical water pipe pressures, therefore not safe for design), Class B, C, and D. The thickness of the pipe can either be gathered from classification and dimension tables (Table 2, Table 3) or Figure 1. The wall thickness has varied over the different standards examined (BS 78 1917, BS 78 1938, AIS 1953, AS A145 1965, AS A146 1965, AS A145 1970, AS 1723 1975). The material properties, including tensile strength, also vary with standards and are shown in Table 5.

[2] Installation at zero years means any pipes installed before 1917 will use data from BS 78 (1917). Installation in Australia started prior to the 1890s, however we could not get information on AWWA C100 (1908). AWWA Standard specifications for cast iron water pipes and special castings. Denver, Colorado, USA, AWWA (American Water Works Association): 1–36..

[3] The 1970 standard was used as a substitute for the 1965 standard and the 1965 standard was not sourced.

[4] Note AIS (1953) uses A, B and C for Class assessment, instead of B, C and D.

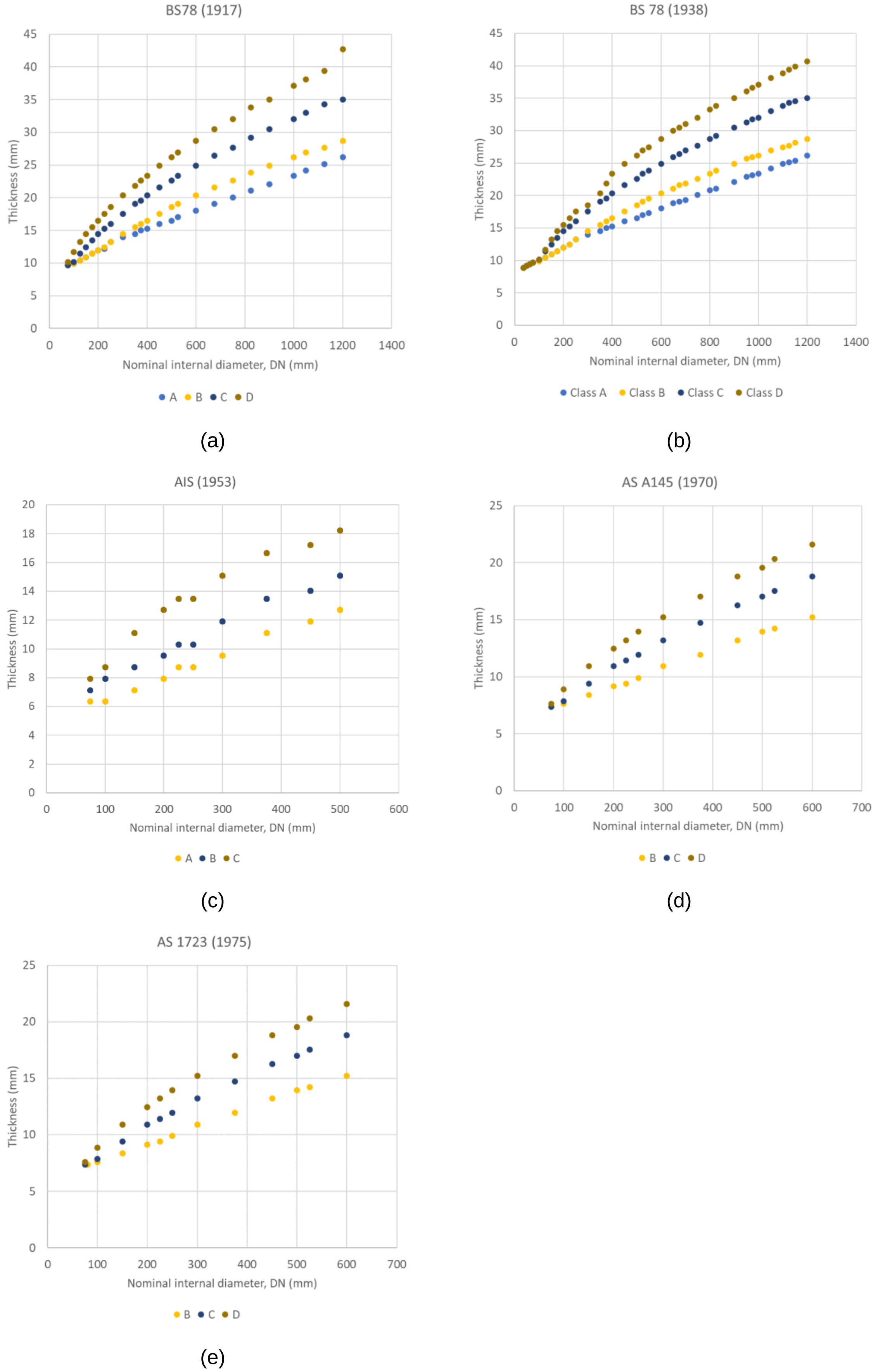

Figure 1. Wall thickness (mm) of CI pipes based on Standards (a) BS 78 (1917), (b) BS 78 (1938), (c) AIS (1953) (d) AS A145 (1970), (e) AS 1723 (1975).

Note that in Cast iron pipes, the wall thickness reduces with newer aged pipes, as the manufacturing techniques improved. Therefore, at different years, different thicknesses will be chosen.

Table 2. Working pressure (MPa) for the relevant CI Class. Adapted from BS 78 (1938).

Working pressure (MPa) Max	Class
0.6	B
0.9	C
1.2	D

The working pressure (Table 2) is compared with the operational pressure of the pipe (or can be manually inputted by the water utility into the model. This operational pressure is used to determine the Class of the pipe. From the class of the pipe the following tables (Table 3) are used to determine both the thickness and the external diameter (tables were from BS78, A145, AS1724). The internal diameter can then be calculated based on:

$$D = D_o - 2T_n$$

where D is the pipe internal diameter, D_o is the pipe external diameter and T_n is the pipe nominal wall thickness.

Table 3. Extract of table of CI pipe Classes and properties.

Material	Standard	DN	Nominal internal diameter of pipe	Mean OD D(mm)	Mean Wall t (mm)	Mean ID (mm)	Nominal working head (m)	Nominal working Pressure (MPa)	Class PN
CI	BS 78 (1917)	75	76.2	95.504	9.7	76.2	61	0.6	B
CI	BS 78 (1917)	100	101.6	121.92	9.9	102.1	61	0.6	B
CI	BS 78 (1917)	125	127	149.86	10.4	129.0	61	0.6	B
CI	BS 78 (1917)	150	152.4	177.292	10.9	155.4	61	0.6	B
CI	BS 78 (1917)	175	177.8	204.724	11.4	181.9	61	0.6	B
CI	BS 78 (1917)	200	203.2	232.156	11.9	208.3	61	0.6	B
CI	BS 78 (1917)	225	228.6	259.08	12.4	234.2	61	0.6	B
CI	BS 78 (1917)	250	254	286.004	13.2	259.6	61	0.6	B
CI	BS 78 (1917)	300	304.8	333.756	14.5	304.8	61	0.6	B
CI	BS 78 (1917)	350	355.6	386.588	15.5	355.6	61	0.6	B
CI	BS 78 (1917)	375	381	413.004	16.0	381.0	61	0.6	B
CI	BS 78 (1917)	400	406.4	439.42	16.5	406.4	61	0.6	B
CI	BS 78 (1917)	450	457.2	492.252	17.5	457.2	61	0.6	B
CI	BS 78 (1917)	500	508	545.084	18.5	508.0	61	0.6	B

Categories of CI pipe are also divided into two, CI and CICL, indicating the presence or non-presence of a cement mortar liner (CML). The typical CML thicknesses were also gathered based on the previous standards. If a CML is present, this will reduce the internal diameter, which will have an effect on the liner dimensions. To account for this, the user can select 3 different CML sizes[5]. The liner thickness categories used are light, medium and heavy.

Table 4. Example of liner thickness for CI and CICL pipes

Material	Lining (CL or U)	Mean CL thickness light tc (mm)	Mean CL thickness medium tc (mm)	Mean CL thickness heavy tc (mm)
CI	U	0		
CICL	CL	3.175	4.7625	6.35

The material properties of CI pipes vary depending on the installation period. The manufacturing processes, Pit cast, spun cast, DeLavaud, Super DeLavaud, etc. all had a bearing on the final material properties and performance (Nicholas and Moore 2009, Shannon et al. 2016, Jiang et al. 2017). Table 5 shows the material properties to be used in the Monash Pipe Evaluation Platform for CI.

Table 5. Material properties for CI pipes

Installation period	σ_t, from standards (MPa)	σ_t, from testing (MPa)	E_p (GPa)	ν_p	K_{IC} (MPa . m$^{1/2}$)
0	124.1	100	85	0.25	13.5
1938	124.1	124	110	0.25	14.5
1953	124	124	110	0.25	15
1965	193	150	110	0.25	16.8
1975	200	200	120	0.25	16.8

Therefore, by knowing the following information:

- Installation year
- DN (diameter) of the pipe
- Operational pressure

The following can be determined (with key data used in the PEP bolded)

- Class of pipe
- **Thickness**
- External diameter
- Internal diameter
- **Material properties**

Alternatively, if the users know some of these data already, they data can be overwritten with the corrected values. For example, a water utility with the following data in (highlighted in green) in Table 6. The following data (in blue) will be prefilled based on the initial information. This is conducted through extracting data from the previous tables. If say Class is already known, this can be overwritten to find the correct wall thickness and diameters.

[5] Note: Some standards provide only one or two CML thicknesses. In this case the liner thickness will be the same for each of the thickness groups. CML have been grouped as: light, medium and heavy.

Table 6. Utility data (green) and prefilled data from the Monash Pipe Evaluation Platform cohort (blue).

Material type	Diameter DN (mm)	Operational pressure (m)	Installation year	Standard	Class	Wall thickness (mm)	External diameter (mm)	Internal diameter (mm)	Tensile strength (MPa)
CI	100	50	1920	BS 78 (1917)	B	9.9	121.9	102.1	100
CI	150	65	1950	BS 78 (1938)	C	12.4	177.3	152.4	124
CI	300	95	1970	AS A145 (1965)	D	15.24	345.44	304.8	193

1.4.2 Asbestos cement pipe cohort

To make the Monash Pipe Evaluation Platform easier for Water Utilities to use, host pipes should be grouped into cohorts to find most relevant material properties and pipe sizes. Supporting information for AC pipes was gathered from Water New Zealand (2017), Water Corporation (2017), Sathiyaseelan et al. (2009), Carroll and Industries (1987), WRF Report 4093 (2013), WRF Report 4093b (2013), Davis et al. (2008). Firstly, the relevant standard is examined to determine further pipe information (Table 1). Three standards were used (BS 486 1933, AS A41 1959, AS 1171 1975) based on British and Australian standards. Information can be gathered from the standards such as wall thickness, pipe diameters, material properties, etc.

Table 7. Installation year and corresponding standard.

Installation period[6]	Standards
0	BS 486 (1933)
1959	AS A41 (1959)
1975	AS 1711 (1975)

For AC pipes there are typically 6 different pressure classes (AS A41 1959, AS 1171 1975), however, typically in the field we would only see pipes in Class C[7] or above (below Class C would be too low for typical water pipe pressures, therefore not safe for design). The thickness of the liner can either be gathered from classification and dimension tables (Table 2, Table 3) or Figure 1. The wall thickness has remained the same over the different standards examined (AS A41 1959, AS 1171 1975). However, the tensile strength and other material properties vary and are shown in Table 5.

[6] Installation of AC pipes in Australia started approximately in the 1930s and production ceased in 1987.

[7] Class A are were typically used for low pressure or non-pressure pipes.

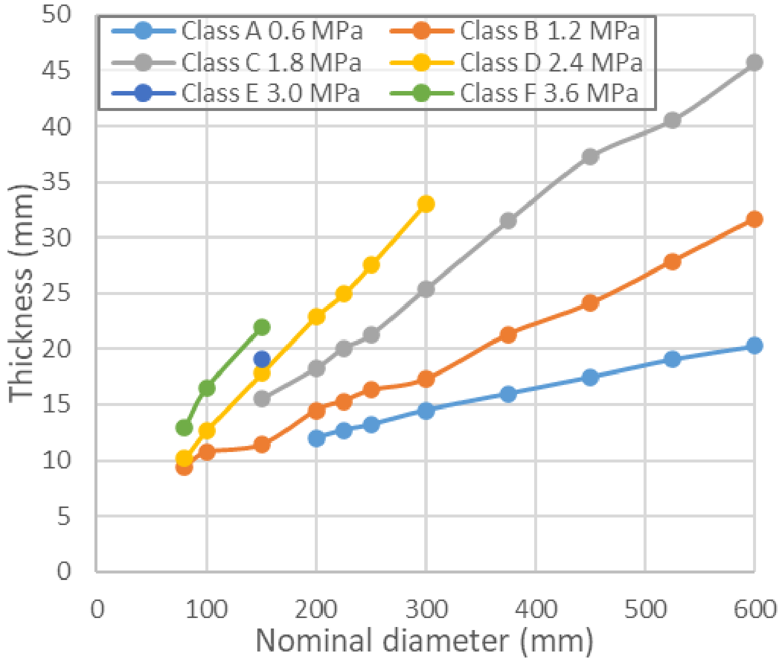

Figure 2. Thickness of AC pipes based on AS1711

Table 8. Working pressure (MPa) for the relevant AC Class. Adapted from AS A41 (1959).

Working pressure (MPa)		
min	max	Class
0	0.3	A
0.3	0.6	B
0.6	0.9	C
0.9	1.2	D
1.2	1.5	E
1.5	1.8	F

The working pressure (Table 2) is compared with the operational pressure of the pipe (or can be manually inputted by the water utility into the Pipe Evaluation platform. This operational pressure is used to determine the Class of the pipe. From the class of the pipe the following tables (Table 3 and Table 10) are used to determine both the thickness and the external diameter (tables were from AS A41 (1959) and AS 1171 (1975)). The external diameter remains constant for each diameter (DN) and pressure class, therefore the internal diameter changes (higher pressure class has smaller internal diameter). The orange values have been excluded as no pipe typical sizes for that class were constructed. The internal diameter can be calculated from the external diameter and the wall thickness.

These sizes are close for pipes installed after 1950 (Water Corporation 2017), before these we use BS standard, however pipe properties could not be found, therefore wall thickness and external diameter are from *(AS A41 1959, AS 1171 1975)* only.

Table 9. Wall thickness of AC pipe Classes (AS A41 1959, AS 1171 1975)

Wall thickness for Class (mm)						
Working pressure (MPa)	0.3	0.6	0.9	1.2	1.5	1.8
DN/Class	A	B	C	D	E	F
58	[8]					10.1[9]
80		9.4		10.2		13
100		10.7		12.7		16.5
150		11.4	15.5	17.8	19.1	21.9
200	12	14.5	18.3	22.9		
225	12.7	15.3	20.1	24.9		
250	13.2	16.3	21.3	27.5		
300	14.5	17.3	25.4	33		
375	16	21.3	31.5			
450	17.5	24.1	37.3			
525	19.1	27.9	40.6			
600	20.3	31.7	45.7			

Table 10. External wall diameter of AC pipe Classes (AS A41 1959, AS 1171 1975)

Outer diameter for Class (mm)						
Working pressure (MPa)	0.3	0.6	0.9	1.2	1.5	1.8
DN/Class	A	B	C	D	E	F
58						77.6
80		95.6		95.6		95.6
100		121.9		121.9		121.9
150		177.3	177.3	177.3	177.3	177.3
200	232.2	232.2	232.2	232.2		
225	259.1	259.1	259.1	259.1		
250	286	286	286	286		
300	333.8	333.8	345.4	345.4		
375	413	413.9	426.2			
450	492.2	492.2	507			
525	571.5	571.5	587.2			
600	650.2	650.2	667			

The internal diameter can then be calculated based on:

$$D = D_o - 2T_n$$

where D is the pipe internal diameter, D_o is the pipe external diameter and T_n is the pipe nominal wall thickness.

[8] All cells highlighted in orange are where no pipes of that standard size were typically manufactured.

[9] DN58 was used for pipes in Western Australia (WA) only

The material properties of AC pipes vary depending on the installation period. The manufacturing processes; Sutton, Mazza, Magnani, Autoclave, etc., all had a bearing on the final material properties and performance (BS 486 1933, AS A41 1959, Allen 1971, AS 1171 1975, Mai 1979, Carroll and Industries 1987, SA Water 2014). Table 5 shows the material properties to be used in the Pipe Evaluation Platform for AC.

Table 11. Material properties for AC pipes

Installation period	Minimum tensile strength, σ_t (MPa)[10]	E_p (GPa)[11]	ν_p	K_{IC} (MPa . m$^{1/2}$)
0	15.5	10	0.15	3.5
1959	22.1	15	0.15	3.5
1975	23.5	20	0.15	3.5

where E_p is the modulus of elasticity of the pipe, ν_p is the Poisson's ratio of the pipe and K_{IC} is the fracture toughness of the pipe.

Therefore, by knowing the following information:

- Installation year
- DN (diameter) of the pipe
- Operational pressure

The following can be determined (with key data used in the PEP bolded)

- Class of pipe
- **Thickness**
- External diameter
- Internal diameter
- **Material properties**

Alternatively, if the users know some of these data already, they data can be overwritten with the corrected values. For example, a water utility with the following data in (highlighted in green) in Table 12. The following data (in blue) will be prefilled based on the initial information. This is conducted through extracting data from the previous tables. If say Class is already known, this can be overwritten to find the correct wall thickness and diameters.

Table 12. Utility data (green) and prefilled data from the Monash Pipe Evaluation Platform cohort (blue).

Material type	Diameter DN (mm)	Operational pressure (m)	Installation year	Standard	Class	Wall thickness (mm)	External diameter (mm)	Internal diameter (mm)	Tensile strength (MPa)
AC	100	50	1936	BS 486	B	10.7	121.9	100.5	15.5
AC	150	62	1960	AS A41	C	15.5	177.3	146.3	22.1
AC	300	95	1970	AS1711	D	33.0	345.4	279.4	23.5

1.4.3 Ductile iron pipe cohort

Can be updated with further research.

[10] Minimum tensile strength has been reported lower than these values in literature, however it is difficult to tell if this is due to manufacturing differences or deterioration.
[11] Elastic modulus values are not well reported in literature. There are also large variations, which could be due to manufacturing, deterioration or anisotropic properties.

For Ductile Iron (DI) pipes cohorts, the relevant standard was examined to determine further pipe information (Table 13). Eight standards (modifications from AS 2280) were used (AS 2280 1979, AS 2280 1988, AS 2280 1991, AS 2280 1995, AS 2280 1999, AS 2280 2004, AS 2280 2012, AS 2280 2014, AS 2280 2020). Information can be gathered from the standards such as minimum wall thickness, pipe diameters, tensile strength, and pipe class.

Table 13. Installation year and corresponding standard for Ductile Iron pipes.

Installation period	Standards
1979	AS 2280 (1979)
1988	AS 2280 (1988)
1991	AS 2280 (1991)
1995	AS 2280 (1995)
1999	AS 2280 (1999)
2004	AS 2280 (2004)
2012	AS 2280 (2012)
2014	AS 2280 (2014)
2020	AS 2280 (2020)

The following table (Table 14Table 18) is used to determine both the thickness and the external diameter. The internal diameter can then be calculated based on:

$$D = D_o - 2T_n$$

where D is the pipe internal diameter, D_o is the pipe external diameter and T_n is the pipe nominal wall thickness.

Table 14. Extract of table of DICL pipe Classes and properties.

Material	Standard	DN	Nominal internal diameter of pipe	Mean OD Do (mm)	Mean wall thickness (mm)	Mean ID (mm)	Nominal working head (m)	Nominal working Pressure (MPa)	Class PN
DICL	AS 2280 (1999)	500	508	560.3	12	536.3	509.7	5	K12
DICL	AS 2280 (1999)	600	609.6	667	13.2	640.6	509.7	5	K12
DICL	AS 2280 (1999)	750	762	826	15	796	509.7	5	K12
DICL	AS 2280 (2004)	225	228.6	259	5	249	204	2	PN20
DICL	AS 2280 (2004)	250	254	286	5	276	204	2	PN20
DICL	AS 2280 (2004)	300	304.8	345	5	335	204	2	PN20
DICL	AS 2280 (2004)	375	381	426	5.1	415.8	204	2	PN20

All ductile iron (DICL) pipes are assumed to be lined with a cement mortar liner (CML). The typical CML thicknesses were also gathered based on the previous standards. A CML will reduce the internal diameter, which will have an effect on the liner dimensions. To account for this, the user can select 3 different CML sizes[12]. The liner thickness categories used are light, medium and heavy. In most cases only a minimum liner thickness was used in standards for ductile iron pipes.

[12] Note: Some standards provide only one or two CML thicknesses. In this case the liner thickness will be the same for each of the thickness groups. CML have been grouped as: light, medium and heavy.

Table 15. Example of liner thickness for DICL pipes

Material	Lining (CL or U)	Mean CL thickness light tc (mm)	Mean CL thickness medium tc (mm)	Mean CL thickness heavy tc (mm)
DICL	CL	3	7	7

The material properties of DI pipes are consistent in standards Table 16 shows the material properties to be used in the Monash Pipe Evaluation Platform for DICL.

Table 16. Material properties for DICL pipes

Installation period	σ_t, from standards (MPa)	E_p (GPa)	ν_p	K_{IC} (MPa . m$^{1/2}$)
0	420	165	0.27	22
1979	420	165	0.27	22
1988	420	165	0.27	22
1995	420	165	0.27	22
1999	420	165	0.27	22
2004	420	165	0.27	22
2014	420	165	0.27	22
2020	400	165	0.27	22

A yield strength of 300 MPa can be substituted for tensile strength if the user requires.

At this stage, users will need to input their own properties for ductile iron pipes including the following information:

- Installation year
- DN (diameter) of the pipe
- Operational pressure

The following will be found from cohort properties

- **Class of pipe**
- **Thickness**
- **External diameter**
- **Internal diameter**
- **Material properties**

Alternatively, if the users know some of these data already, they data can be overwritten with the corrected values.

1.4.4 Mild steel pipe cohort

Can be updated with further research.

For Mild steel (MS) pipes cohorts, the relevant standard was examined to determine further pipe information (Table 17). Six standards were used (AS A125 1963, AS 1281 1972, AS 1579 1973, AS 1579 1993, AS 1579 2001). Information can be gathered from the standards such as minimum wall thickness, pipe diameters, tensile strength, and yield strength.

Table 17. Installation year and corresponding standard for Mild Steel pipes.

Installation period	Standards
0[13]	AS A125 (1963)
1971	AS A125 (1971)
1972[14]	AS 1281 (1972)
1973	AS 1579 (1973)
1993	AS 1579 (1993)
2001	AS 1579 (2001)

The following table (Table 18) is used to determine both the thickness and the external diameter. The internal diameter can then be calculated based on:

$$D = D_o - 2T_n$$

where D is the pipe internal diameter, D_o is the pipe external diameter and T_n is the pipe nominal wall thickness. In most cases only a minimum liner thickness was used in standards for mild steel pipes. The mean wall thickness has been selected based on minimum sizes used in two water utilities in Australia. This size was selected on the utilities minimum wall thickness sized used and should be noted that the utilities also used larger wall thicknesses.

Table 18. Extract of table of MS pipe Classes and properties.

Material	Standard	DN	Nominal internal diameter of pipe	Mean OD D(mm)	Mean Wall thickness (mm)	Mean ID (mm)	Nominal working head (m)	Nominal working Pressure (MPa)	Class PN
MS	AS A125 (1963)	100	102	114.3	5	104.3	694.2	6.81	68
MS	AS A125 (1963)	150	152	168.3	5	158.3	694.2	6.81	68
MS	AS A125 (1963)	200	203	219.1	5	247	694.2	6.81	68
MS	AS A125 (1963)	225	228.6	257	5	263	516.2	6.81	68
MS	AS A125 (1963)	250	254	273	5	326.6	694.2	6.81	68
MS	AS A125 (1963)	300	305	323.9	5	104.3	435.1	6.42	64

Categories of MS pipe are also divided into two, MS and MSCL, indicating the presence or non-presence of a cement mortar liner (CML). The typical CML thicknesses were also gathered based on the previous standards. If a CML is present, this will reduce the internal diameter, which will have an effect on the liner dimensions. To account for this, the user can select 3 different CML sizes[15]. The cement mortar liner thickness categories used are light, medium and heavy.

Table 19. Example of liner thickness for MS and MSCL pipes

Material	Lining (CL or U)	Mean CL thickness light tc (mm)	Mean CL thickness medium tc (mm)	Mean CL thickness heavy tc (mm)
MS	U	0	0	0
MSCL	CL	3	7	7

[13] Further information is required within these years. No standard was found prior to 1963.
[14] Standard for the thickness of cement mortar lining
[15] Note: Some standards provide only one or two CML thicknesses. In this case the liner thickness will be the same for each of the thickness groups. CML have been grouped as: light, medium and heavy.

The material properties of MS pipes vary depending on the grade of the steel used and the installation period. However, the material properties, have been taken as constant for all mild steel pipes. The yield strength of the steel can range from 250 MPa to 300 MPa. Table 20 shows the material properties to be used in the Monash Pipe Evaluation Platform for MS.

Table 20. Material properties for MS pipes

Installation period	σ_t, from standards (MPa)	σ_y, from standards (MPa)	E_p (GPa)	ν_p	K_{IC} (MPa . m$^{1/2}$)
0	400	300	200	0.28	28
1971	400	300	200	0.28	28
1972	400	300	200	0.28	28
1973	400	300	200	0.28	28
1993	400	300	200	0.28	28
2001	400	300	200	0.28	28

At this stage, users will need to input their own properties for steel pipes including the following information:

- Installation year
- DN (diameter) of the pipe
- Operational pressure

The following will be found from cohort properties

- **Approximate thickness**
- **External diameter**
- **Internal diameter**
- **Material properties**

Alternatively, if the users know some of these data already, they data can be overwritten with the corrected values.

2 SOIL COHORTS

2.1 Introduction

The following soil information is important in the Monash Pipe Evaluation Platform. Four soil properties are used in the Platform: Soil type, Soil modulus, Soil friction angle, Soil unit weight. Secondary soil parameters, such as corrosion rates, can be gathered from soil information. Background information on each of the soil properties are shown below.

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).

Soil modulus (E_s) - The soil modulus or modulus of elasticity or Young's modulus of soil is an elastic soil parameter used in the settlement, compression or movement of soils. Soil modulus is the slope of stress-strain curve in the elastic deformation region for the soil. Units are in MPa. The soil modulus varies with different soil types. Approximate soil modulus values are based on AS 2566.1 (1998).

Soil friction angle (Φ) - The soil friction angle is the angle of internal friction of the soil grains. It is the ability of a soil or rock to withstand shear stress. The friction angle varies between different soil types, such as clay, silt and sand. For a given soil, it is the angle on the graph (Mohr's Circle) of the shear stress and normal effective stresses at which shear failure occurs. The drained friction angle is used for the purpose of our calculations. Units are in degrees (°).

Lateral earth pressure coefficient (k) (at rest) - The lateral earth pressure coefficient at rest and can be calculated by:

$$k = 1 - \sin \Phi$$

where Φ is the soil friction angle.

Soil unit weight (γ_s) - Soil unit weight is 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. The values are typically between 15 kN/m^3 to 20 kN/m^3. Units are in kN/m^3.

2.2 Soil cohort properties

The following table (Table 21) is used in the Monash Pipe Evaluation Platform for soil cohort properties. This includes all soil properties and a further column indicating likely corrosivity for metallic pipes. The likely corrosivity rates are used to assign corrosion rates for metallic pipes (Table 22). Approximate soil modulus values are based on AS 2566.1 (1998) and are likely to be conservative. $\boldsymbol{E_s}$ was taken from the higher range of values of E'_e and E'_n in Table 3.2 (AS 2566.1 1998) due to the soil being in its natural state (trenchless installation with still in-situ soil and host pipe can be assumed as soil is in a dense state). Friction angles were gathered from typical soil properties and used to determine the lateral earth pressure coefficient. The likely corrosivity of the soil was gathered from Deo et al. (2019).

Table 21. Soil type and general soil properties used in the Monash Pipe Evaluation Platform.

Soil type	**Soil modulus, E_s (MPa)**	**Friction angle, Φ (°)**	**Lateral earth pressure coefficient, k**	**Soil unit weight, γ_s (kN/m^3)**	**Likely corrosivity**
Gravel	20	35	0.43	19	Very low
Sand	14	35	0.43	17	Very low
Loamy sand	14	35	0.43	17	Very low
Sandy loam	14	35	0.43	17	Very low
Fine sandy loam	14	32	0.47	20	Low
Loam	10	32	0.47	20	Low
Silty loam	10	30	0.50	20	Moderate
Sandy clay loam	10	30	0.50	20	Moderate
Fine sandy clay loam	10	25	0.58	18	High
Clay loam	10	25	0.58	18	High
Silty clay loam	10	25	0.58	18	High
Sandy clay	10	20	0.66	18	Very high
Light clay	7	20	0.66	18	Very high
Silty clay	7	20	0.66	18	Very high
Medium clay	7	20	0.66	18	Very high
Heavy clay	7	20	0.66	18	Very high

Table 22. Corrosion categories and corrosion parameters used for cast iron and metallic pipes (Deo et al. 2019).

Soil corrosivity category	**r_s (mm/y)**	**c_s (mm)**	**τ (y)**
Very low	0.0042	1.95	15
low	0.021	9.75	15
Moderate	0.0252	11.7	15
High	0.0294	13.65	15
Very high	0.0336	15.6	15

Further information on corrosion rates can be found in UM M2 – Pipe failure analysis.

NOTATION

c_s	Intercept parameter for long-term corrosion of metallic pipes (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)
h	Pressure head (m)
k	Lateral earth pressure coefficient
K_{IC}	Fracture toughness of host pipe material (MPa $m^{1/2}$)
L_p	Length of the pipe (m)
L_{ps}	Length of the pipe spool (m)
$MAOP$	Maximum allowable operational pressure (MPa)
N	Safety factor for host pipe
P	Operating pressure (MPa)
PN	Nominal pressure (bar)
P_T	Test pressure (MPa)
P_c	Recurring cyclic surge pressure (MPa)
P_s	Surge pressure (MPa)
P_v	Vacuum pressure (MPa)
r_s	Minimum corrosion rate (long-term) of metallic pipes (mm/y)
t	Time (years)
T	Pipe wall thickness allowing for uniform corrosion (mm)
T_f	AC pipe remaining wall thickness at failure (mm)
T_n	Pipe nominal wall thickness (mm)
γ_s	Soil unit weight (kN/m^3)
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 (°)

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 Liner Selection 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.

CONCLUSIONS

This document provided the theory of the Pipe and soil cohorts used in the Monash Pipe Evaluation Platform. Increasing model accuracy will allow more accurate prediction of the pipe remaining service life based on deterioration models, and better recommendations on suitable renovation techniques and predictions of the likely increase in service life a renovation technique may provide. This in turn will allow utilities to target spending more accurately, deferring capital expenditure where possible, while also improving customer service through fewer interruptions.

Utilities should require recording of pipe class (or wall thickness) and material strength (yield strength) for all new pipe records. It would benefit utilities to obtain data for existing pipes, through records or from field inspection. Though the cost of data collection must be balanced against the benefits.

Further pipe cohorts such as Ductile iron, Mild steel, the PVC variants, concrete, etc. can be analysed and included if further research is conducted.

Soil cohort properties are given and can be used to prefill values for the Monash Pipe Evaluation Platform.

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