Engineering

Critical Pipe Project
Activity 4e – Probabilistic Physical Modelling
Progress Presentation

Prof. Jayantha Kodikara
Dr. Jian Ji

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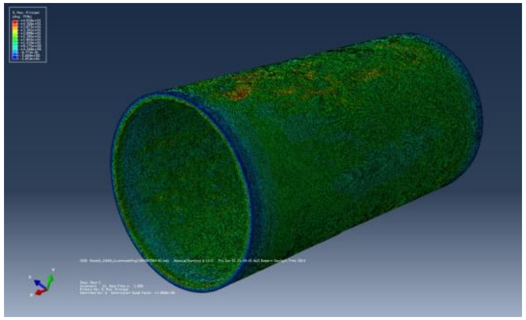
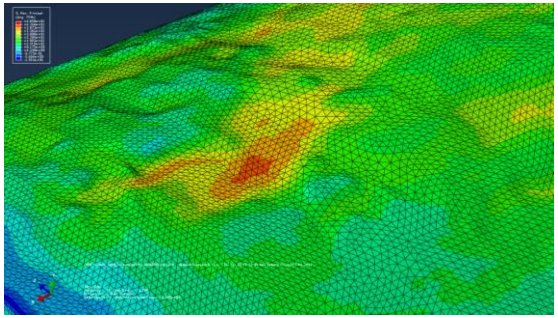
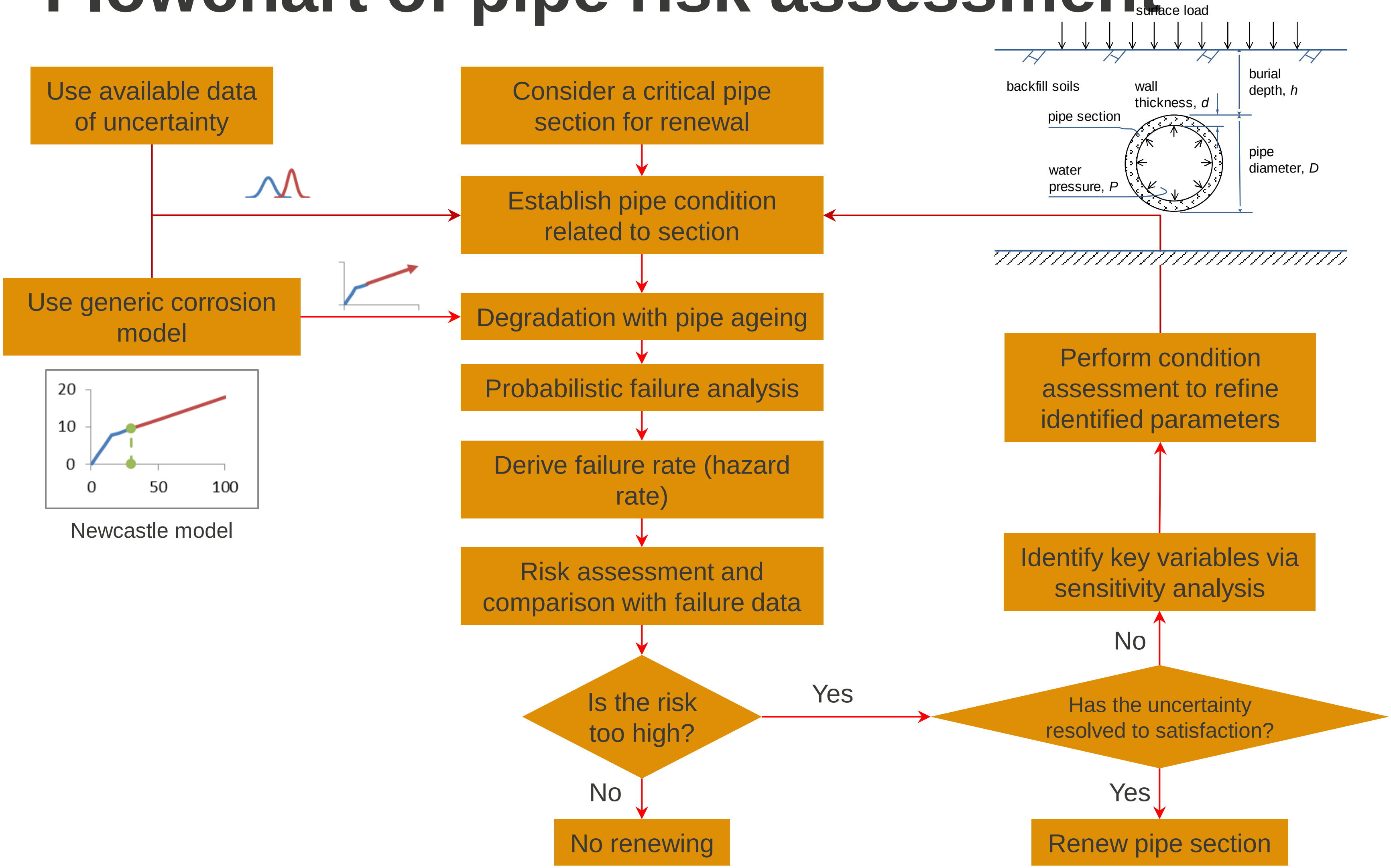




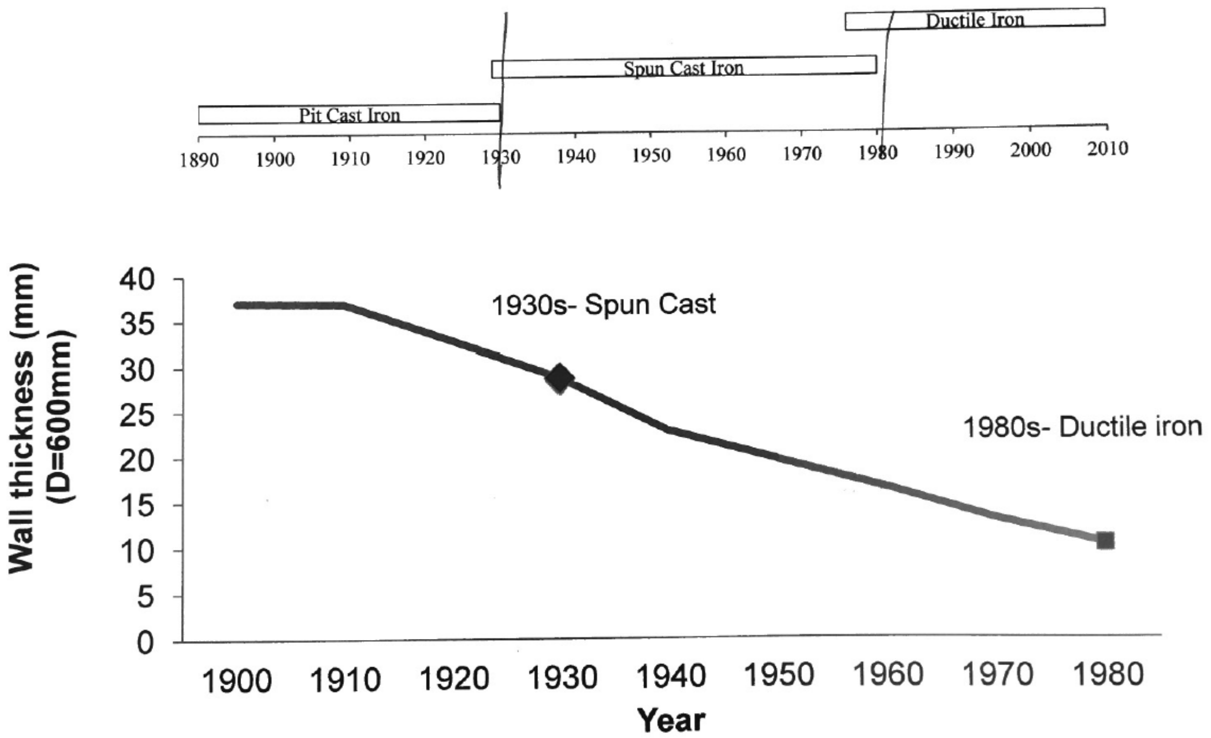
Overview

- Part 1: Review of key physical properties and their statistical analyses
- Part 2: Probabilistic physical modelling (PPM): Methodology
- Part 3: Cohort hazard prediction by PPM: Results
- Part 4: Summary

Flowchart of pipe risk assessment



Literature review- dimensions of CI Pipes

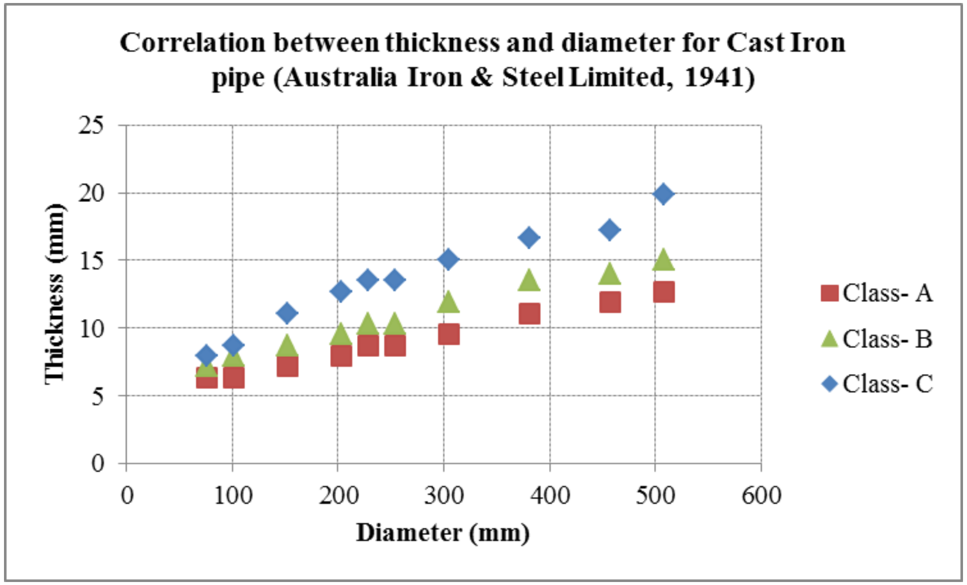


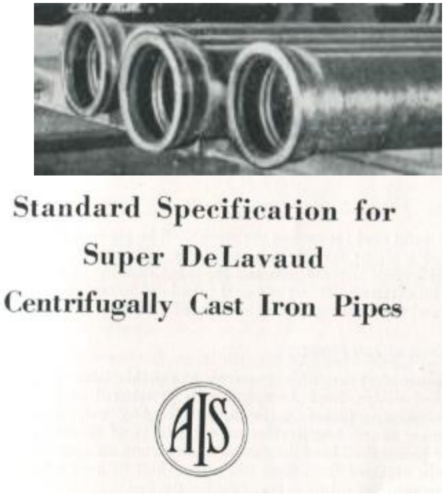
- Pit cast: Bigger wall thickness, but lower tensile strength
- Spun cast: Smaller wall thickness, but higher tensile strength

Part 1: Review of key physical properties and their statistical analyses

Correlation between pipe diameter and thickness

Historical data from manufacturer, AIS, 1941





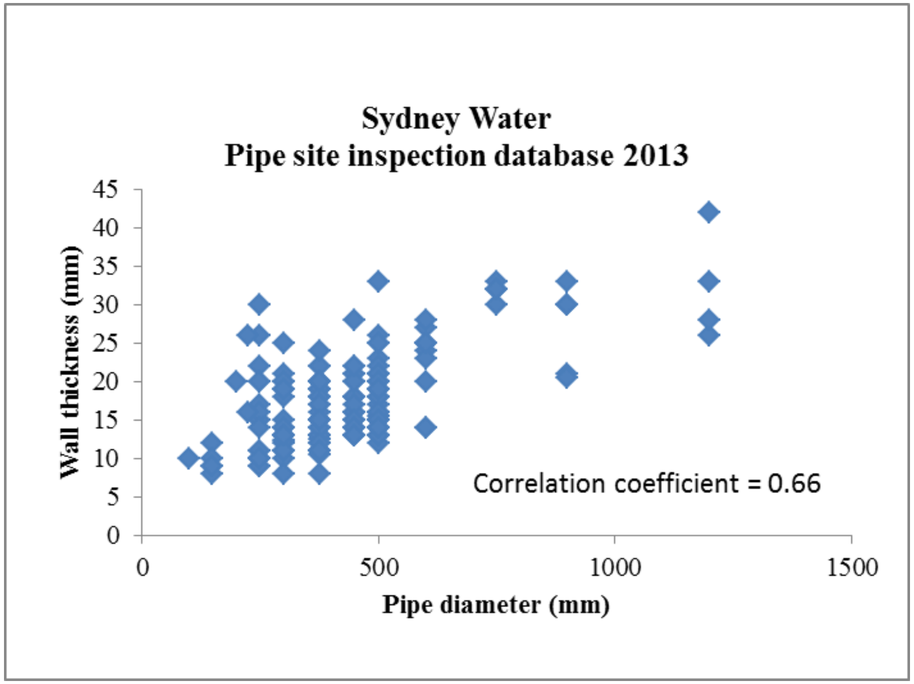
Correlation coefficent:

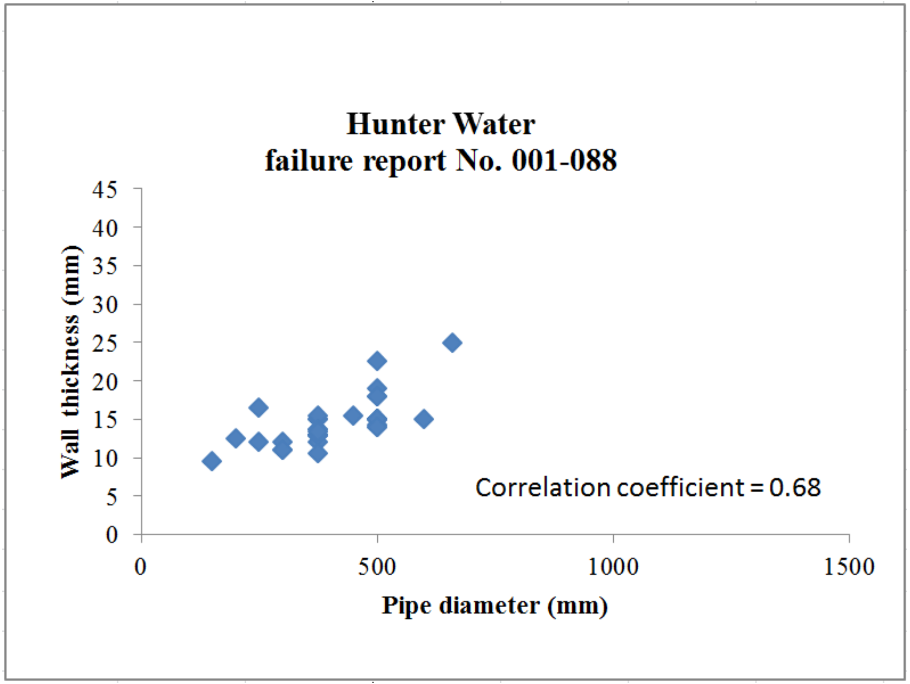
0.98 (Class- A)

0.99 (Class- B)

0.98 (Class- C)

Historical data from utility site inspection

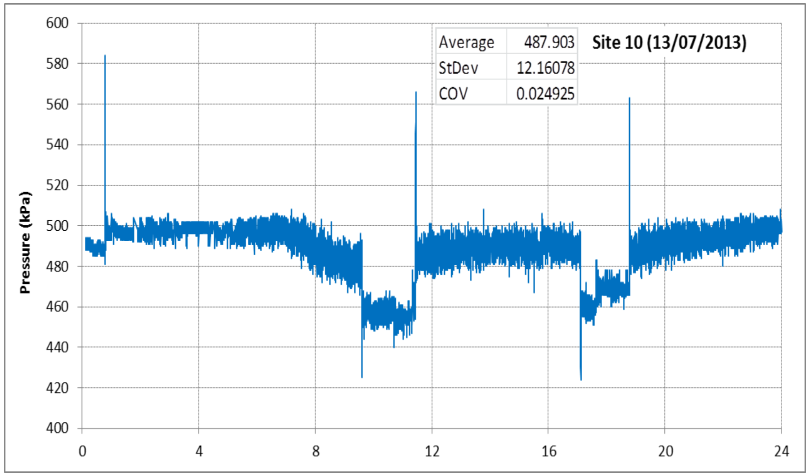




Need to get right data in cohort analysis

Variation of water pressure at a test site - Lookout long-term

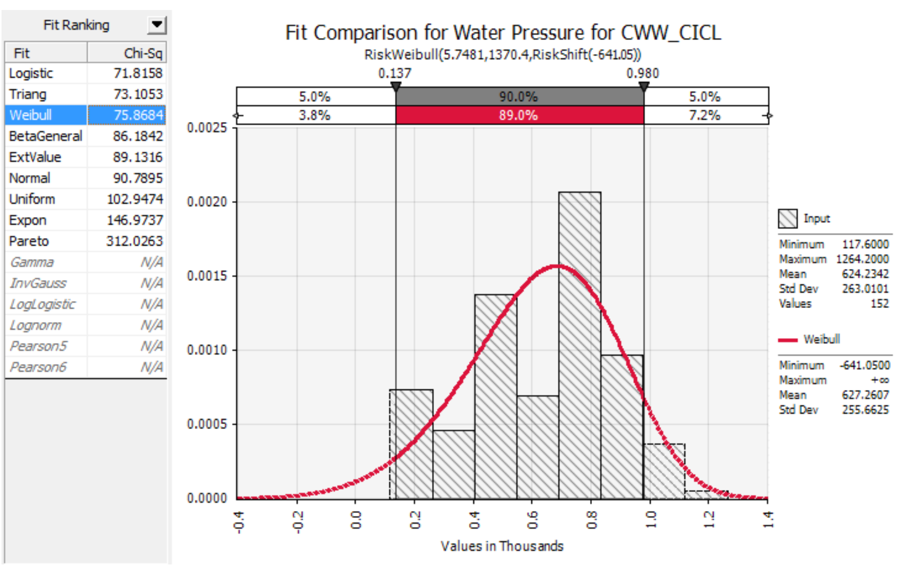
1. Water pressure at a test site consists of transient and steady-state pressures.
2. Due to large volume of steady-state record data, these peak values representing the transient could be unrealistically averaged, hence unable to characterize the variation.

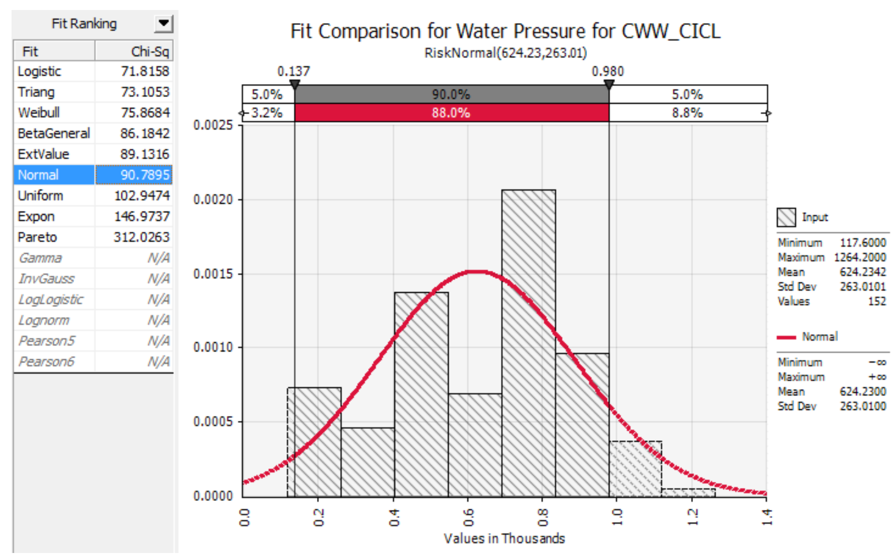


3. It is more realistic to seperate the transient and operational pressure

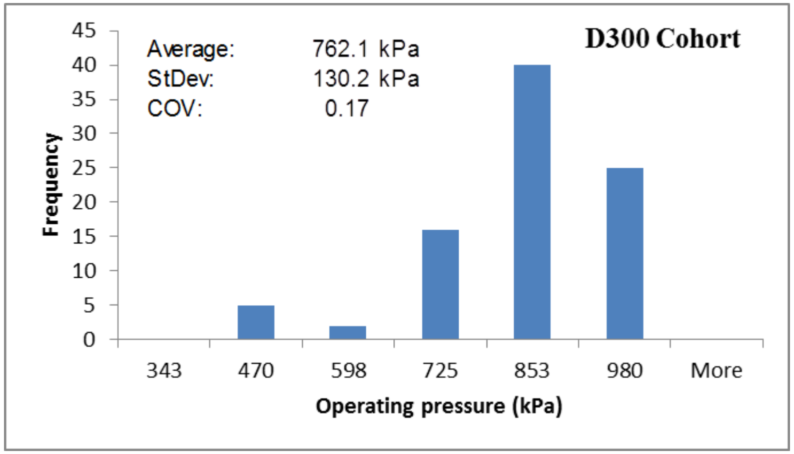
Statistics of water pr in CICL Cohort

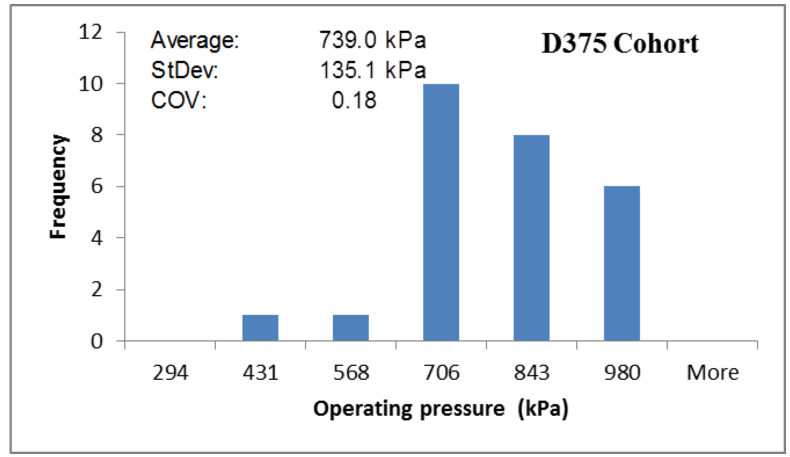
Observation: Water pressure for pipe cohort of the same material but mixed diameter has relatively larger coefficient of variation, typically varying up to 0.42; Several statistical distributions may be fitted to the data, including Triangular, Weibull, Normal or LogNormal. It seems there is no priority of one to others. For simplicity, Normal or LogNormal is sufficient for probabilistic physical modelling

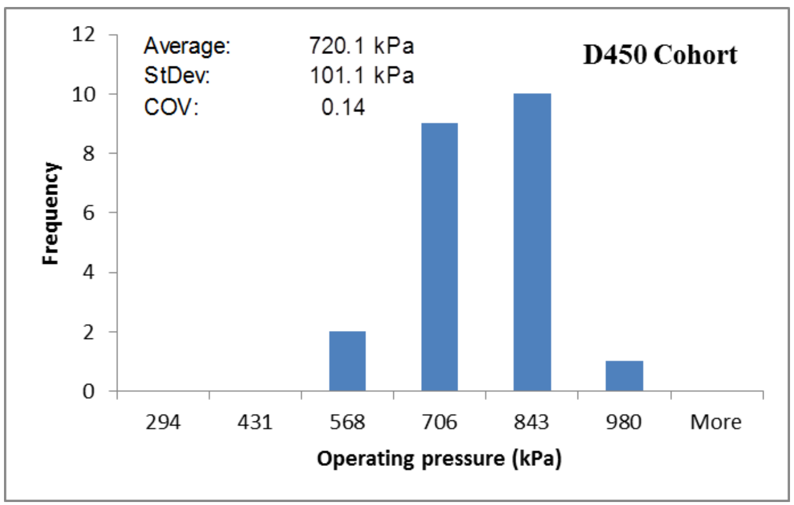




Variation of water pr in pipe cohort of the same diameter







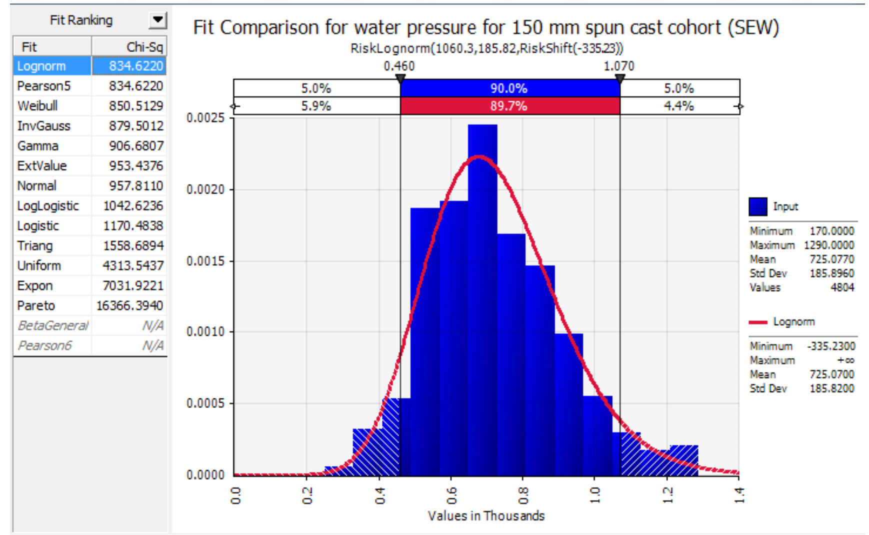
Reference: City West Water data

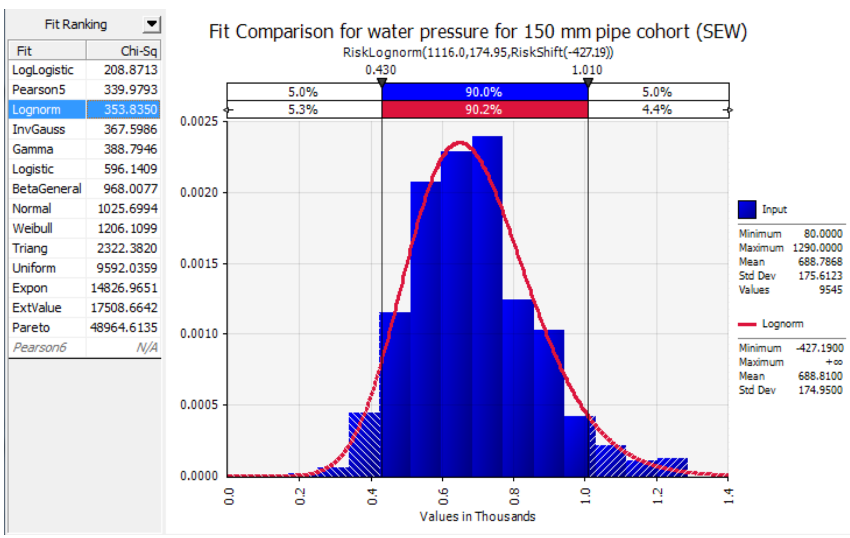
water-main failures for Monash critical data since 1997

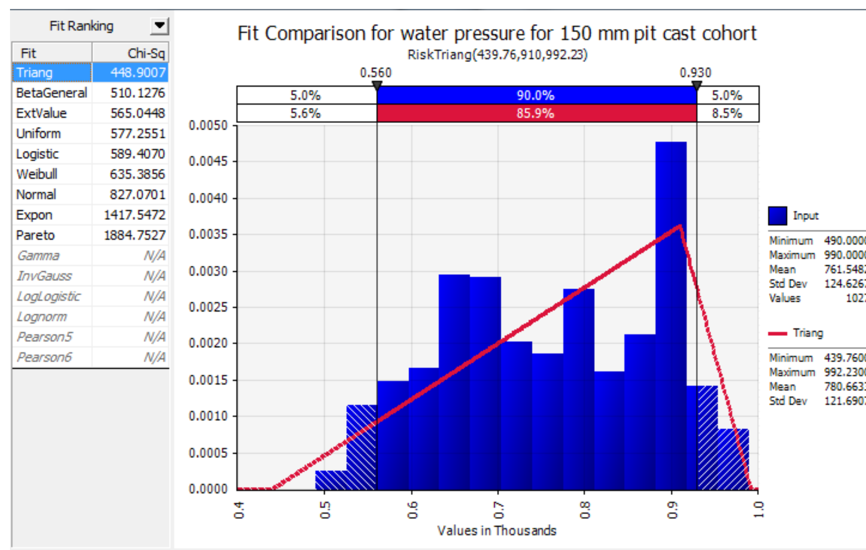
Observation: Water pressure for pipe cohort of the same diameter has relatively low coefficient of variation, typically varying between 0.15 to 0.20

Statistics of water Pr in SEW CICL Cohort

Observation: Coefficient of Variation for operating water pressure in pipelines is around 0.25







Statistical analysis of CI tensile strength 1

- Statistics of tensile strength for an isolated test pipe

Pipe diameter = 500 mm
Sample type: uniform

Pit CI pipe in burst test Sydney

4 samples

σ_t = 103 MPa

Spun CI pipe in H' street

4 samples,

σ_t = 135 MPa

Currently, data for tensile strengths are limited.

Need more test results to fill the gaps.

- Taken from the same pipe, the samples do not show much variation w.r.t. tensile strength. The coefficient of variation is reasonably assumed less than 0.15.

Statistical analysis of CI tensile strength 2

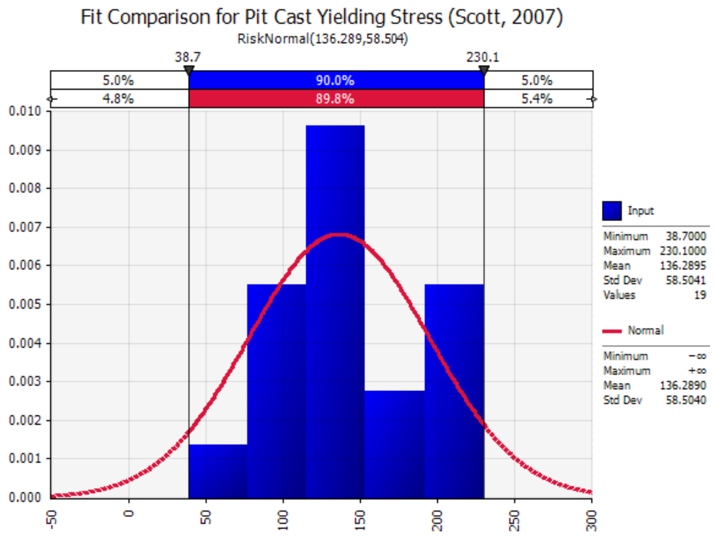
- Tensile strength for cast iron pipe cohorts (Scott 2007)

Pipe diameter = 100 mm
Sample type: corroded specimens

Pit cast iron

Fit Ranking

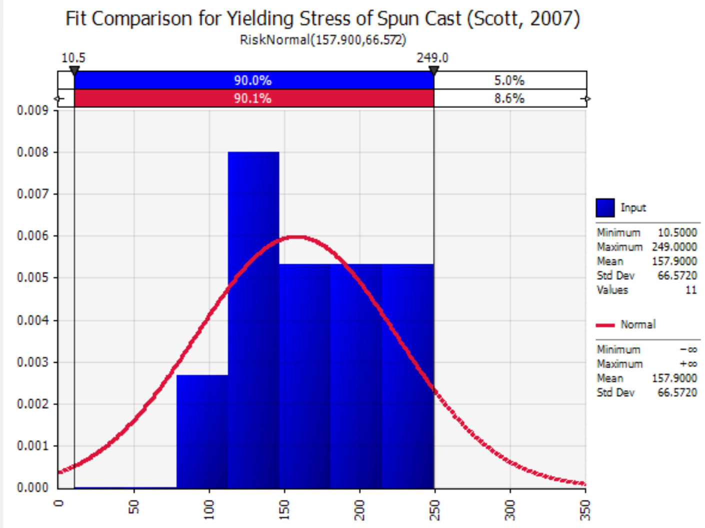
Fit	Chi-Sq
ExtValue	0.1579
Normal	0.5789
InvGauss	1.0000
Logistic	1.0000
LogLogistic	1.0000
Lognorm	1.0000
Pearson5	1.0000
Weibull	1.0000
Triang	3.1053
Uniform	3.1053
Expon	6.0526
BetaGeneral	10.0526
Pareto	11.5263
Gamma	*N/A*
Pearson6	*N/A*



Spun cast iron

Fit Ranking

Fit	Chi-Sq
ExtValue	0.0909
Logistic	0.0909
Normal	0.0909
Triang	0.0909
Weibull	0.0909
BetaGeneral	0.4545
Uniform	2.2727
Expon	7.3636
Pareto	9.1818
Gamma	*N/A*
InvGauss	*N/A*
LogLogistic	*N/A*
Lognorm	*N/A*
Pearson5	*N/A*
Pearson6	*N/A*

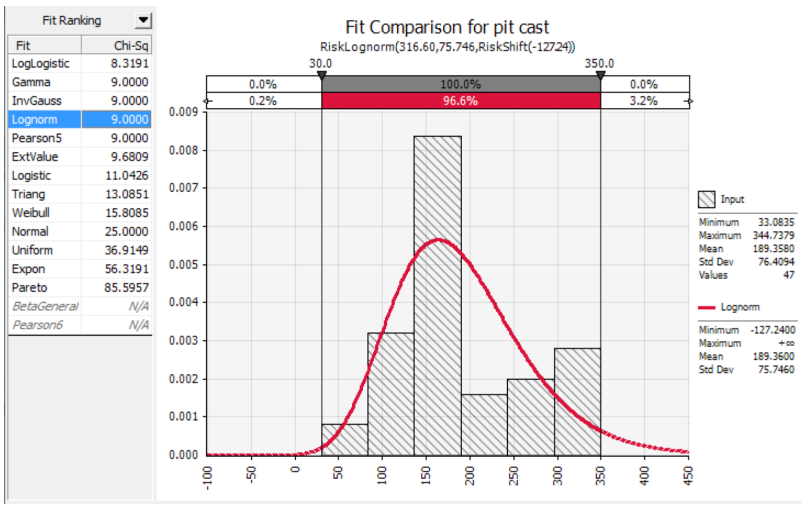


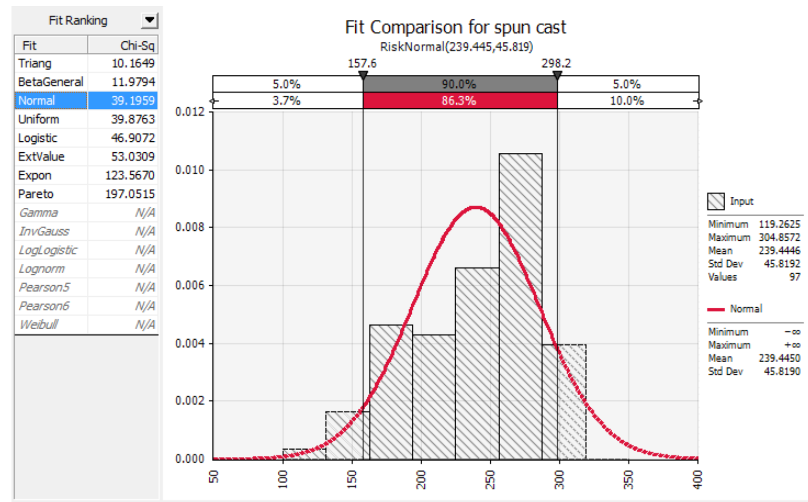
- On average, the tensile strengths are 136 MPa for pit cast, and 158 MPa for spun cast iron. The percentage difference is 16 %. Both pit cast and spun cast iron pipes are subjected to high coefficient of variation (c.o.v.) of value up to 40%

Statistical analysis of CI tensile strength 3

- Tensile strength for cast iron pipe cohorts (Rajani 2012)

Canadian
Material type: Corroded specimens ?



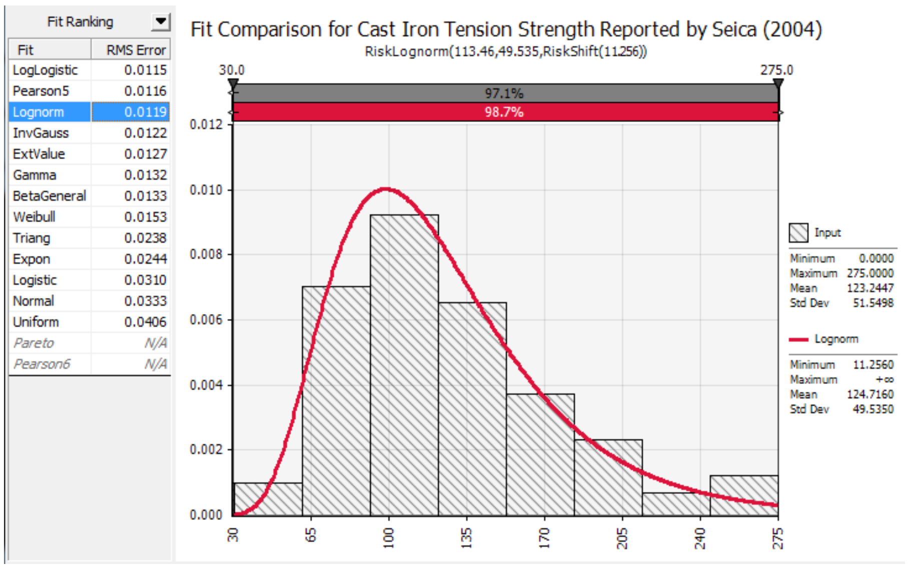


- The average tensile strengths are 189 MPa for pit cast, and 239 MPa for spun cast iron. Also, both pit cast and spun cast iron pipes are subjected to high variation in the tensile strengths. The c.o.v. is up to 40% for pit cast, and 20% for spun cast iron pipes.

Statistical analysis of CI tensile strength 4

- Tensile strength for cast iron pipe cohorts (Seica & Packer, 2004)

North America
Material type: Corrosion ?



- The tensile strength is 123 MPa for cast iron (mixed type). Again, the c.o.v. is up to 40%.

Summary of pipe physical statistics - 1

- For analysis of individual pipes:
  - Water pressure: mean value varies from 500 kPa to 1100 kPa, coefficient of variation is 0.15
  - Tensile strength
    - Australia large diameter CI pipes: mean value is 100 MPa for pit cast, and 130 for spun cast materials. Both are subject to coefficient of variation of 0.15
    - For overseas: average tensile strength seems to be higher by 30 to 50%. What are the implications of this?
    - To fill the gap, we need to conduct more experiments to investigate the Australia CI pipe tensile strength
  - Wall thickness and pipe diameter: mean value depends on the diameter, coefficient of variation is 0.1

Summary of pipe physical statistics - 2

- For analysis of pipe cohorts in the network:
  - Water pressure: mean value varies from 500 kPa to 1100 kPa, coefficient of variation is 0.25
  - Australia large diameter CI pipes Tensile strength: mean value is 100 MPa for pit cast, and 130 for spun cast materials. Both are subject to coefficient of variation of 0.4
  - Pipe diameter: mean value depends on the cohort, coefficient of variation is 0.1
  - Wall thickness: mean value depends on the diameter, coefficient of variation is 0.25

Part 2: Probabilistic Physical Modelling: Methodology

(Bottom-up approach)

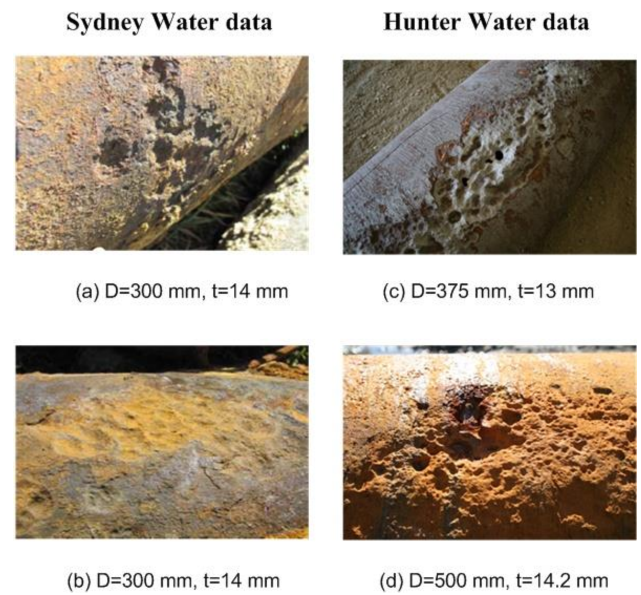
Pipe stress prediction on pitting corrosion pipes

Type of corrosion

- **Pitting corrosion (Type – III)** refers to localised regions of metal loss that can be characterised by pit geometry.

(A)

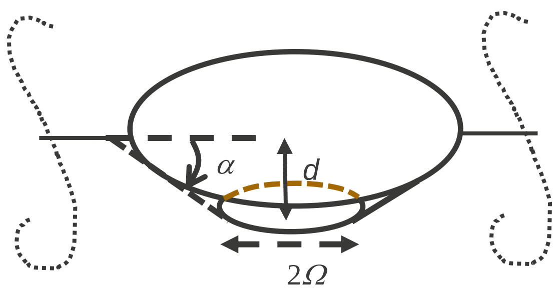
(B)

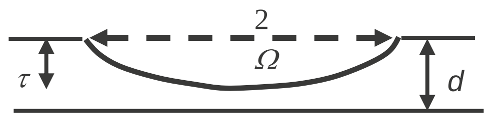


(C)

Effect of Patch Corrosion in Pipe Stress

Non-Linear regression model for stress concentration factor (circular)

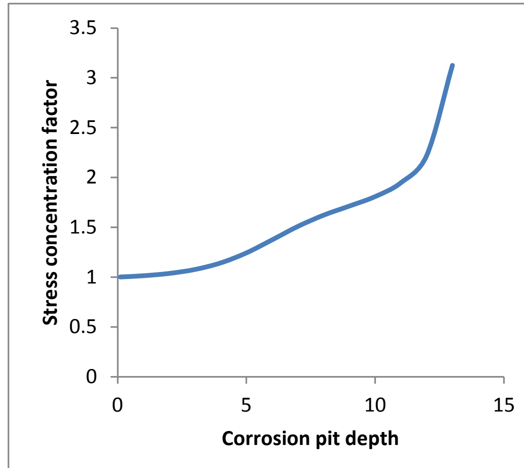


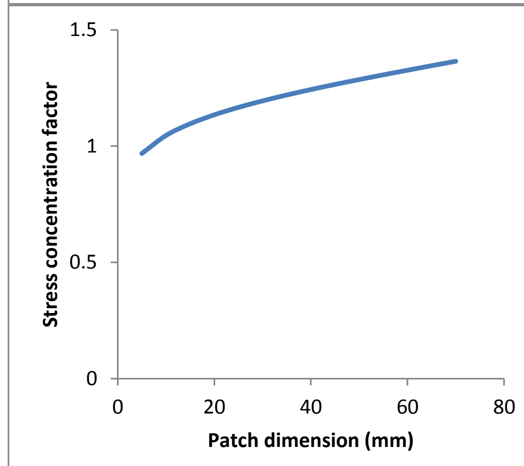


$$SCF_{TWC} = 5.4998 \times \left\{ \frac{\sqrt[4]{3(1-\nu^2)}}{2} \cdot \left(\frac{\Omega}{\sqrt{Rd}} \right)^{1.2} \cdot \left(\frac{1}{\sin\alpha} \right)^{1.5} \right\}^{0.3377}$$

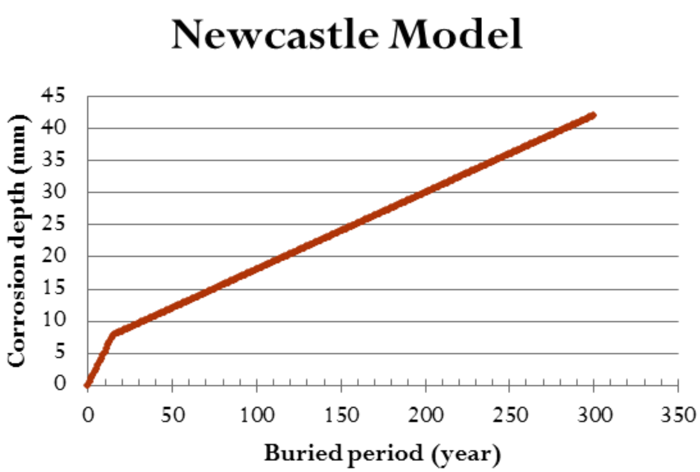
$$SCF_{RWC} = \frac{\left\{ 1.0 - \alpha_1 \left[1.0 - \left(d'/d \right)^{\alpha_2} \right] . M(\Omega, d, R, d', \nu) \right\}}{\left\{ 1.0 - \alpha_1 \left[1.0 - \left(d'/d \right)^{\alpha_2} \right] \right\}}$$

$$\sigma(\mathbf{x}, t) = \sigma_{nom} \times SCF(t)$$





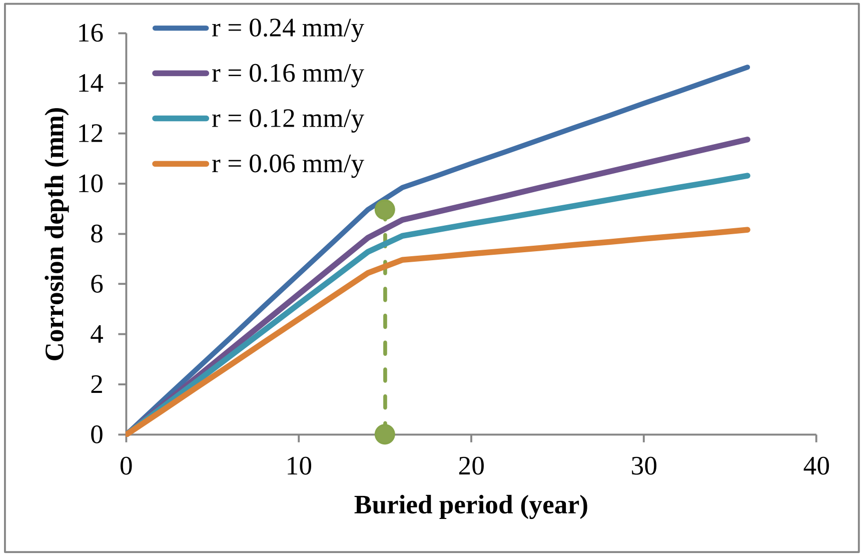
Corrosion pit depth v.s. pipe ageing



$$\begin{cases} \tau(t) = c_s + r_s \times t, & \text{when } t \geq T^* \\ \tau(t) = (c_s / T^* + r_s) \times t, & \text{when } t < T^* \end{cases}$$

Assume	Cs=	6mm
	rs=	0.12
	T*=	15

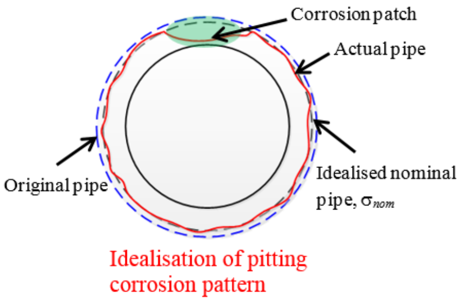
- Bilinear corrosion model



Coupling the pitting corrosion to uniform wall thickness loss

- Buried water mains are usually subjected to complex corrosion patterns. Typically, there could be some critical pits scattered on a uniformly corroded pipe wall. This combined corrosion patterns need to be properly considered in the pipe failure mechanism.
- The following assumptions apply in this probabilistic physical modelling:

  1) The uniform loss of wall thickness is reasonably assumed to be 1/5 of the **most critical pit depth**.
  2) The isolated corrosion pit is circular from top-view
  3) The pit dimensions (radius) will linearly (e.g., 5 times) increase with pit depth



Typical statistical information of physical properties in pipeline analysis

Physical parameter		Mean value	COV (Others)	Distribution	Source of data
Location	Bury depth, h	0.8 m	0.25	Normal	ACA&PFPP
Backfill soil surrounding pipelines	Elastic modulus, Es	25 MPa	0.3	LogNormal	Common assumptions
	Unit weight	20 kN/m3	0.1	LogNormal	
Pipe physical properties (cast iron)	Elastic modulus	100 GPa	0.05	LogNormal	Common assumptions
	Yielding stress	100 MPa	0.1	Normal	Seica and Packer (2004), ACA&PFPP
	wall thickness	12 to 35		Normal	AIS (1941), ACA&PFPP
	Pipe diameter	Varying		Normal	
Load	Surface load (traffic)	50 kN	0.3	Normal	ACA&PFPP
	Operating water pressure	1000 kPa	0.15	Normal	ACA&PFPP
Corrosion	cs	6 mm	0.3	LogNormal	Newcastle
	rs	0.12 mm/y	0.3	LogNormal	
	T*	15 y	0.01	Normal	
Pit size	λ_{u1}	5*pit_depth mm	0.5	Normal	Typical values inferred from Hunter Water pipeline failure report, ACA&PFPP
	λ_{u1}	5*pit_depth mm	0.5	Normal	
	λ_{b1}	4*pit_depth mm	0.5	Normal	
	λ_{b1}	4*pit_depth mm	0.5	Normal	

Probabilistic physical modelling of pitting corrosion pipe

- Stress prediction of cast iron pipe by finite element analysis
- Stress concentration factor of corrosion pit
- Bilinear corrosion model from activity 3
- Time-dependent limit state function:

$$g(\mathbf{x},t) = \sigma_y - \sigma_{nom}(\mathbf{x},t) \cdot SCF(t)$$

- Probability of pipe failure:

$$P\{g(\mathbf{x},t) < 0\} = P\{\sigma_y - \sigma_{nom}(\mathbf{x},t) \cdot SCF(t)\}$$

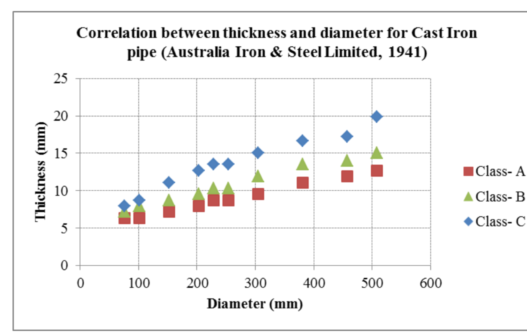
Standard pipe thickness for Sydney Water

Water Main Pipe Thicknesses

CICL	100	150	200	250	300 Class B	300 Class C	375 Class B	375 Class C	450 Class B	450 Class C	500 Class B	500 Class C	600 Class B	600 Class C	750	900
1880's																
1890's			17		14.5 ^	21		16	17.5	24						
1900's									17.5	24						
1910's									17.5	24		22.6				
1920's					14.5 ^			16			18.5 ^		20.3 ^	24.9		30.5
1930's			10.3		11.9 ^		13.5 ^				15.1 ^					
1940's							13.5 ^		14.02							
1950's	7.9	8.7			11.9		13.5 ^				15.1 ^		20.3 ^			
1960's											17 *	15.1				
1970's													18.9^			
1980's																

Data Sources
- Class B (CI BS 1938) - British Standard Specification for Cast Iron Pipes BS78, 1938, British Standard Institution
- Class B (CI AIS 1941) - Cast Iron Pipes, 1941, Australian Iron & Steel Ltd
- Class B (AS 1723 1967);

Typical values provided by Sydney Water



Cohort-based failure prediction by PPM

- A series of charts for failure prediction have been developed for cohorts
- Various scenarios of operating water pressure and corrosion rate are included
- Case combinations:
  - Average cohort diameter 300, 375, 450, 500, 600 mm
  - Average operating water pressure 500, 700, 900, 1100 kPa
  - Average corrosion rate 0.08, 0.12, 0.16 mm/year which respectively denote weak, moderate, and strong corrosion circumstances.

Part 3: Cohort hazard prediction by PPM: Results

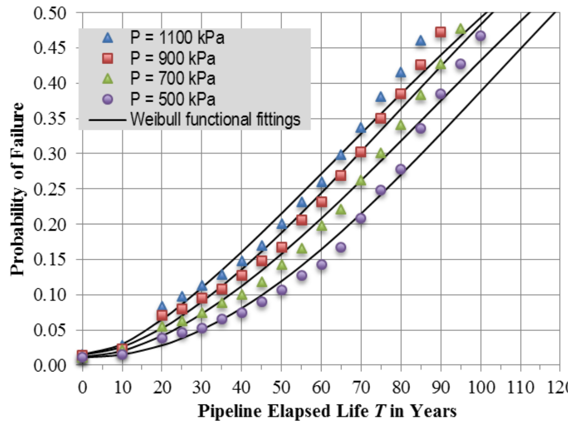
Hazard prediction for spun cast cohorts

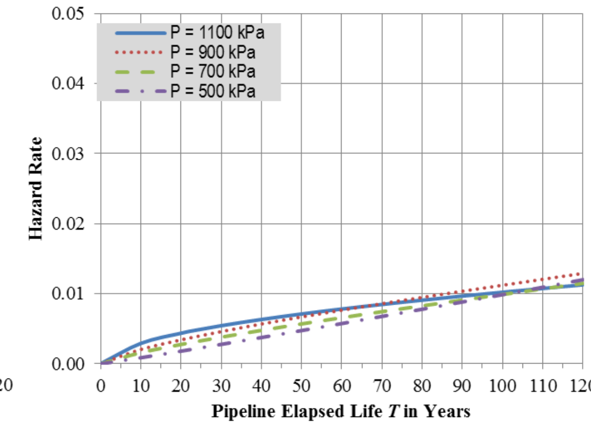
300 mm spun cast iron pipe cohort (Class C)

To refine the analysis, more information is needed on:

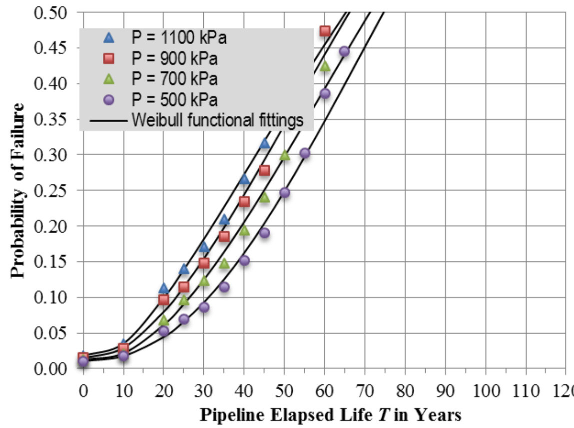
1) Pipe wall thickness
2) CI tensile strength
3) Lateral corrosion rates

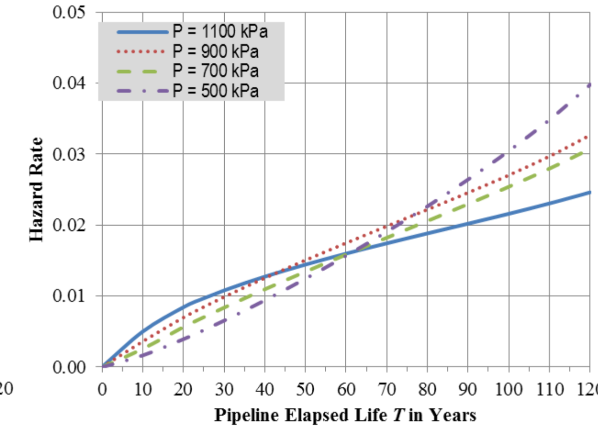
- Subjected to weak corrosion
  r = 0.08 mm/year



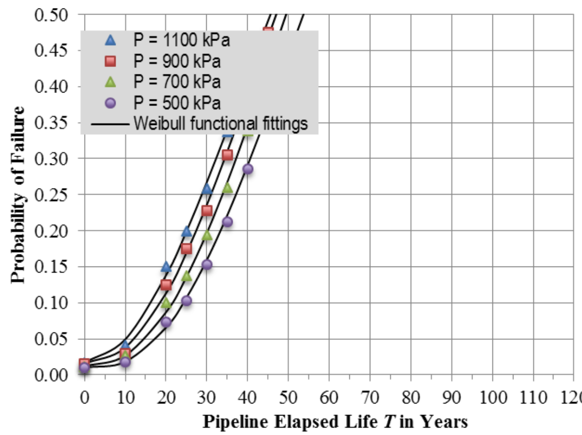


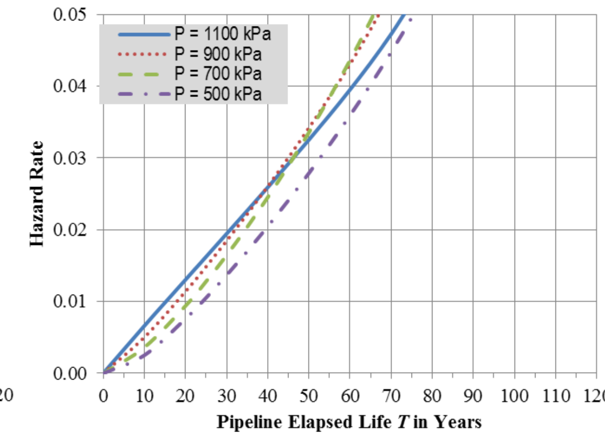
- Subjected to moderate corrosion
  r = 0.12 mm/year





- Subjected to strong corrosion
  r = 0.16 mm/year



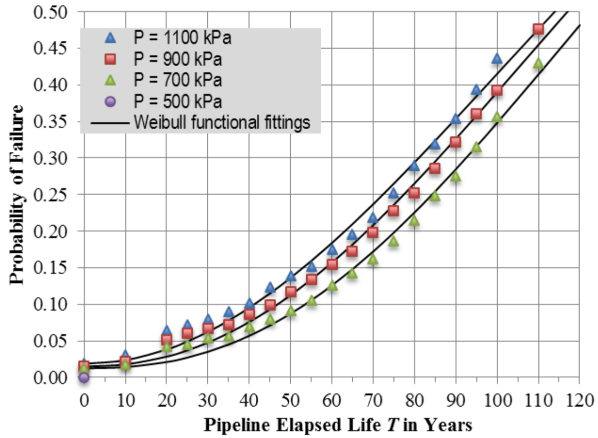


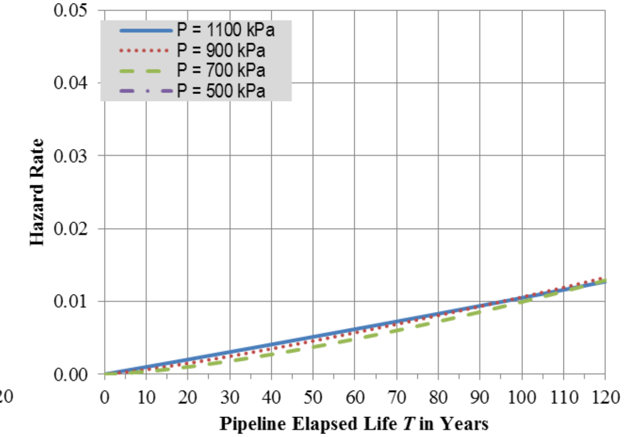
375 mm spun cast iron pipe cohort (Class C)

Some information need to refine:

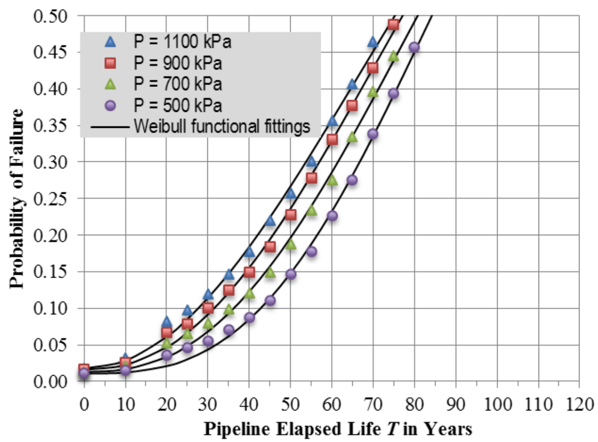
1) Pipe wall thickness
2) CI tensile strength
3) Lateral corrosion rates

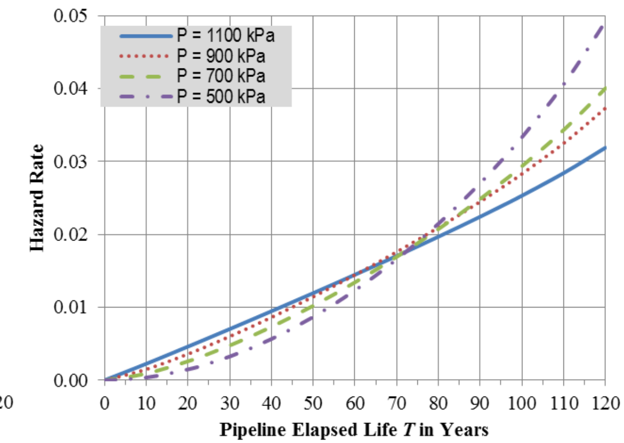
- Subjected to weak corrosion
  r = 0.08 mm/year



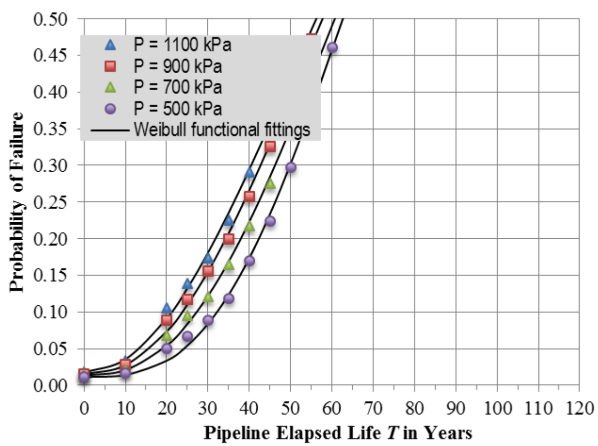


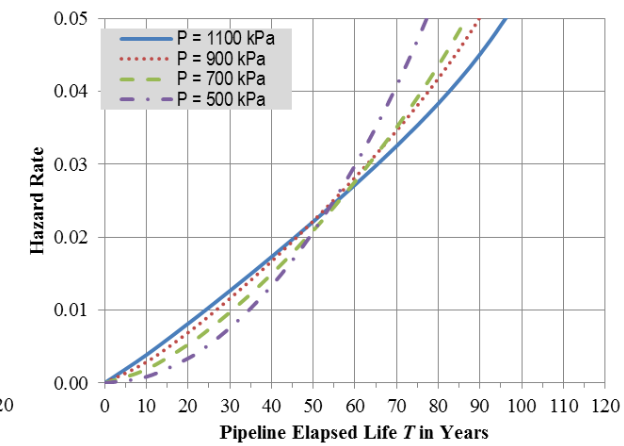
- Subjected to moderate corrosion
  r = 0.12 mm/year





- Subjected to strong corrosion
  r = 0.16 mm/year



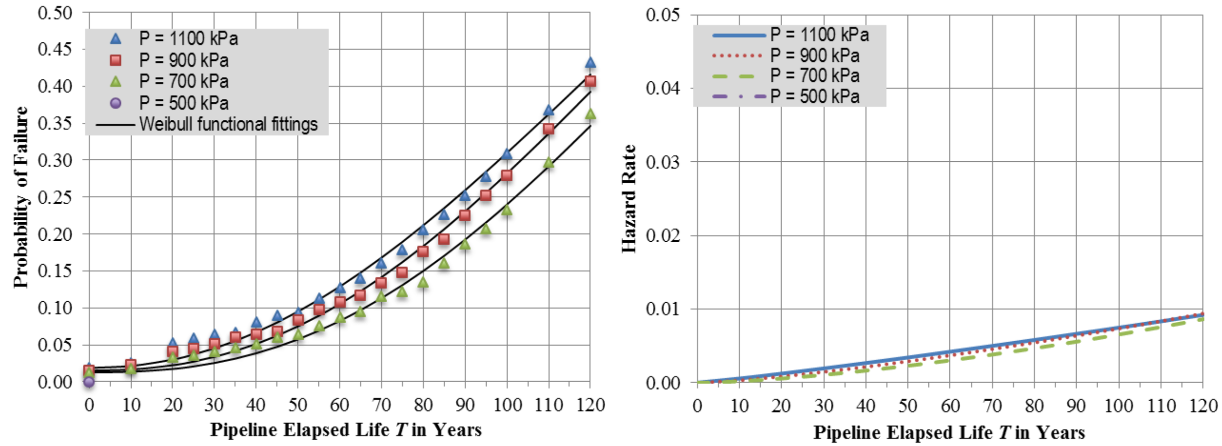


450 mm spun cast iron pipe cohort (Class C)

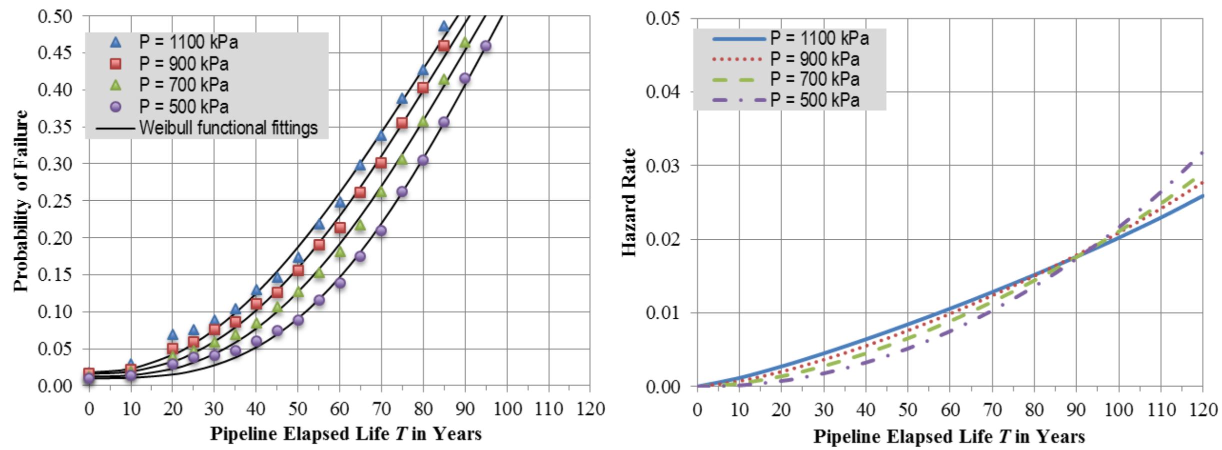
Some information need to refine:

1) Pipe wall thickness
2) CI tensile strength
3) Lateral corrosion rates

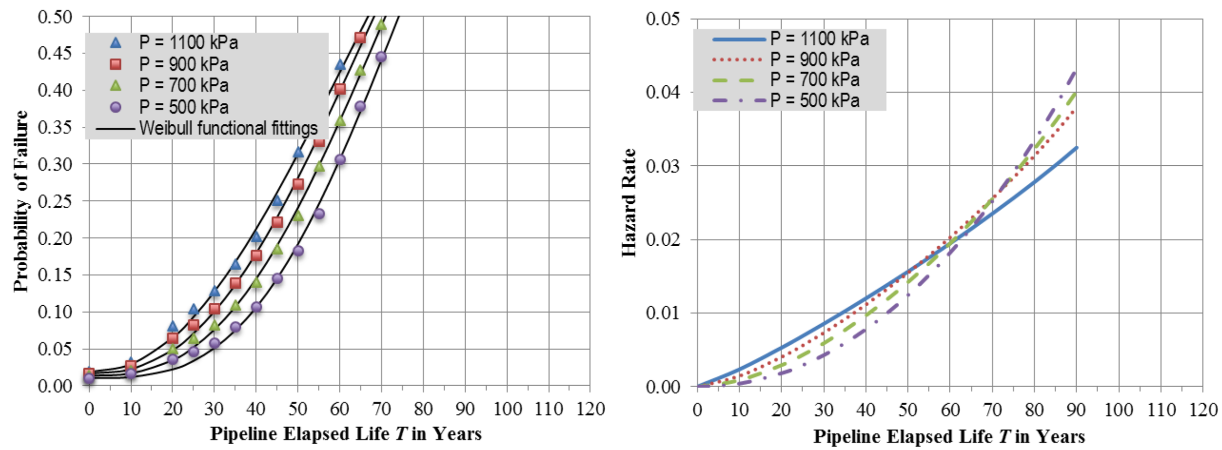
- Subjected to weak corrosion
  r = 0.08 mm/year



- Subjected to moderate corrosion
  r = 0.12 mm/year



- Subjected to strong corrosion
  r = 0.16 mm/year

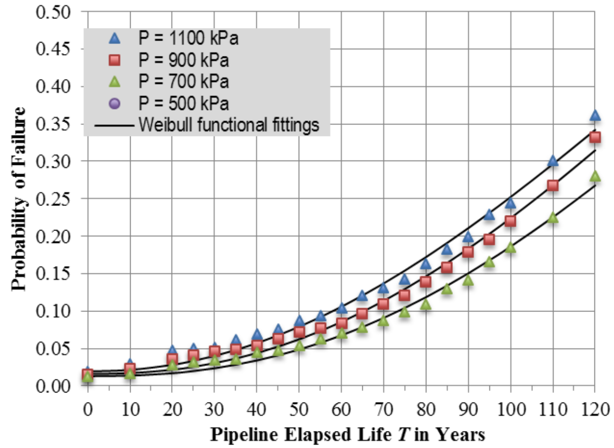


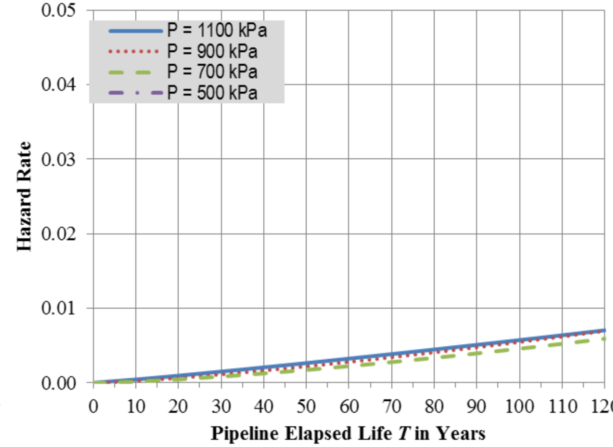
500 mm spun cast iron pipe cohort (Class C)

Some information need to refine:

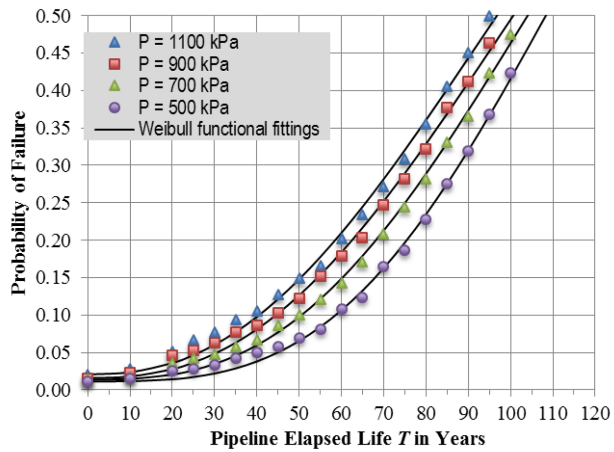
1) Pipe wall thickness
2) CI tensile strength
3) Lateral corrosion rates

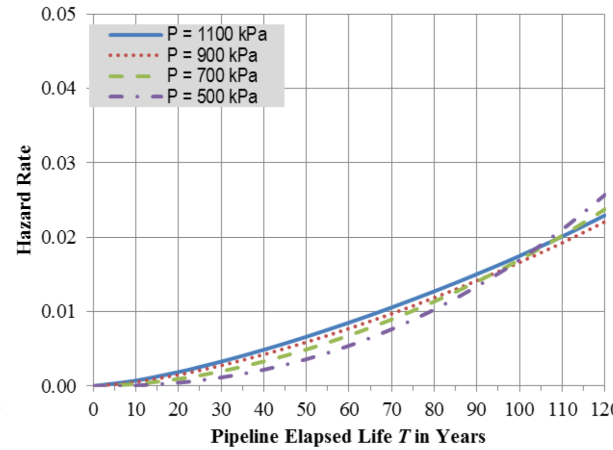
- Subjected to weak corrosion
  r = 0.08 mm/year



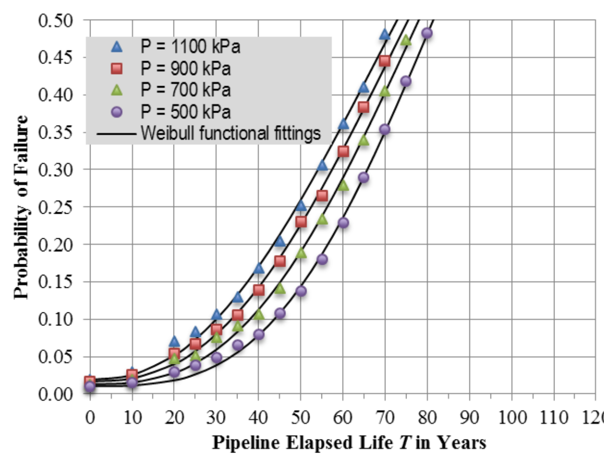


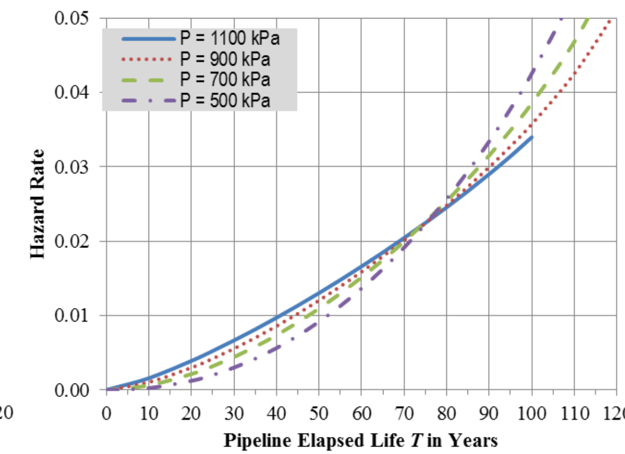
- Subjected to moderate corrosion
  r = 0.12 mm/year





- Subjected to strong corrosion
  r = 0.16 mm/year



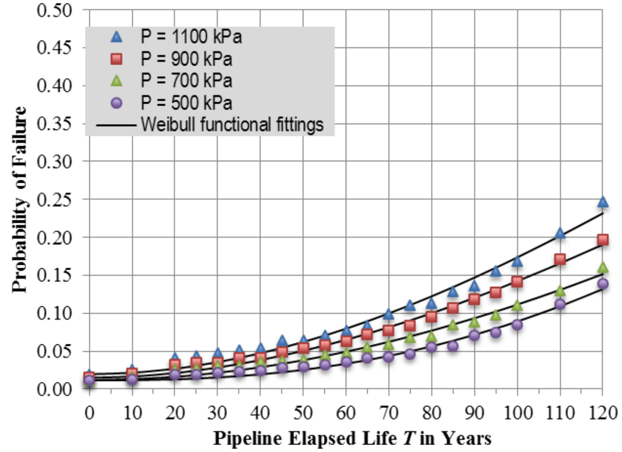


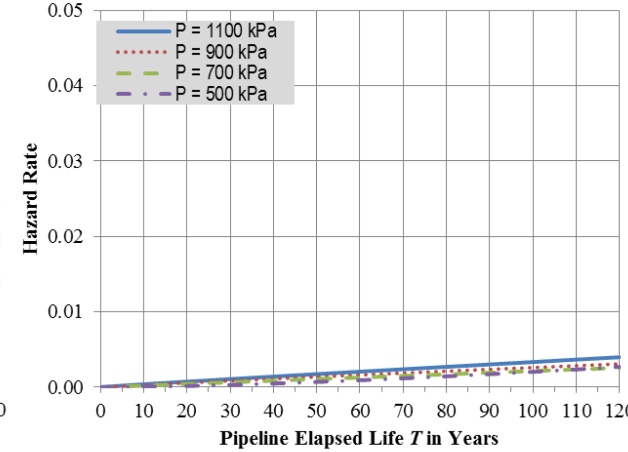
600 mm spun cast iron pipe cohort (Class C)

Some information need to refine:

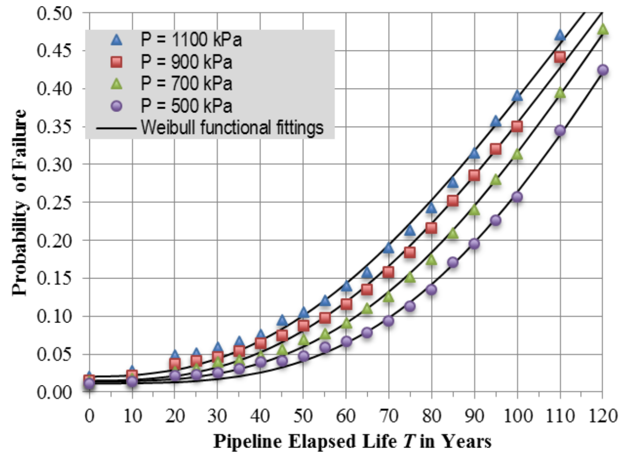
1) Pipe wall thickness
2) CI tensile strength
3) Lateral corrosion rates

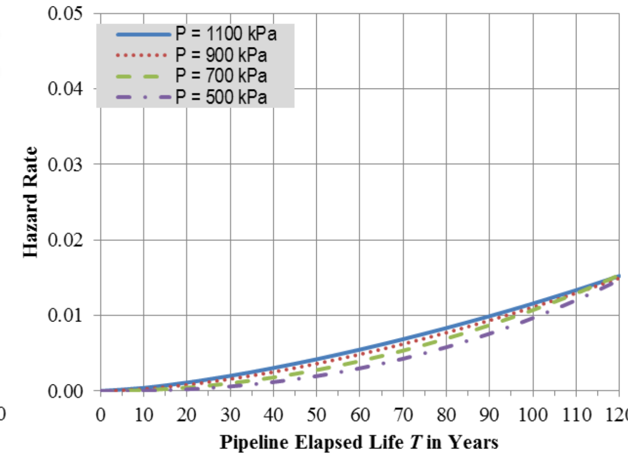
- Subjected to weak corrosion
  r = 0.08 mm/year



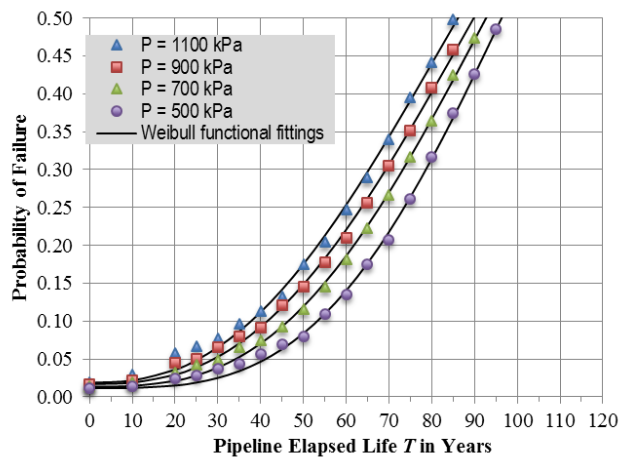


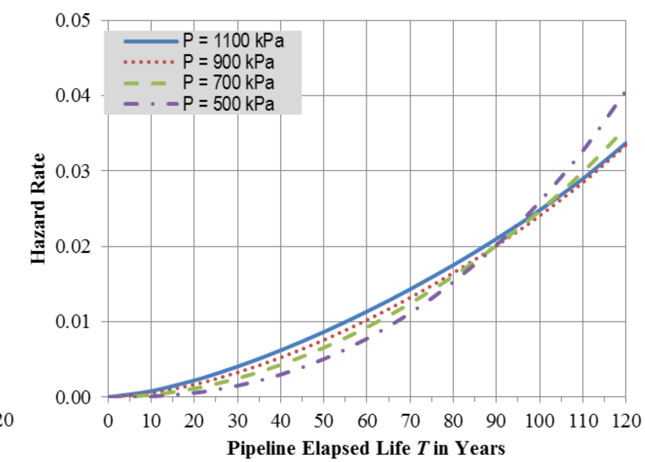
- Subjected to moderate corrosion
  r = 0.12 mm/year





- Subjected to strong corrosion
  r = 0.16 mm/year





Hazard prediction for pit cast cohorts

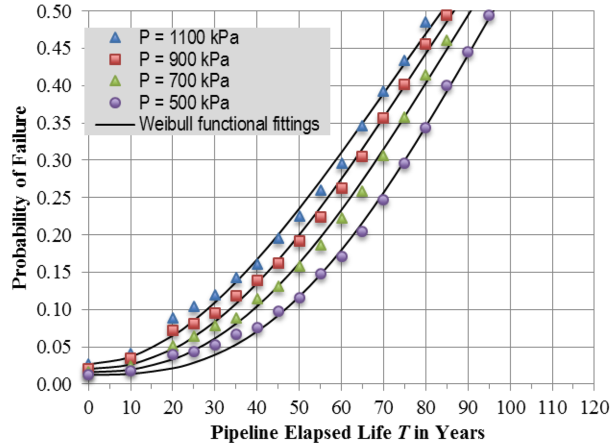
450 mm pit cast iron pipe cohort (Class C)

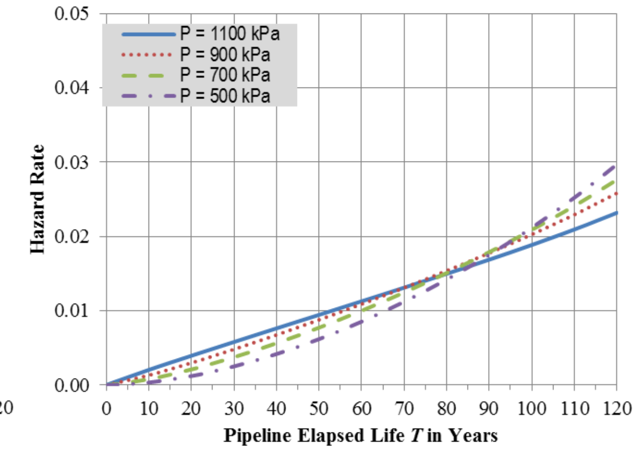
Some information need to refine:

1) Pipe wall thickness
2) CI tensile strength
3) Lateral corrosion rates

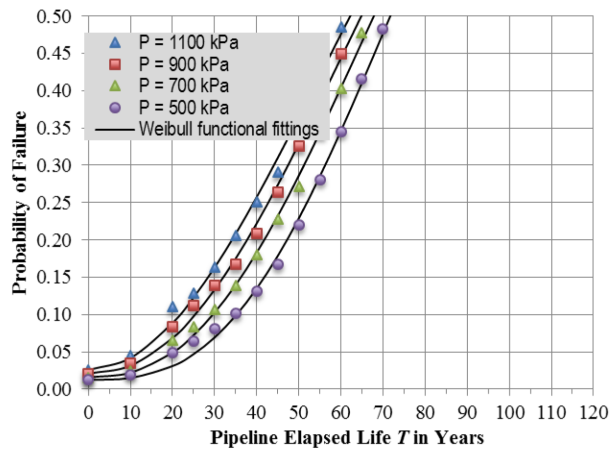
Part 3: Cohort hazard prediction by PPM

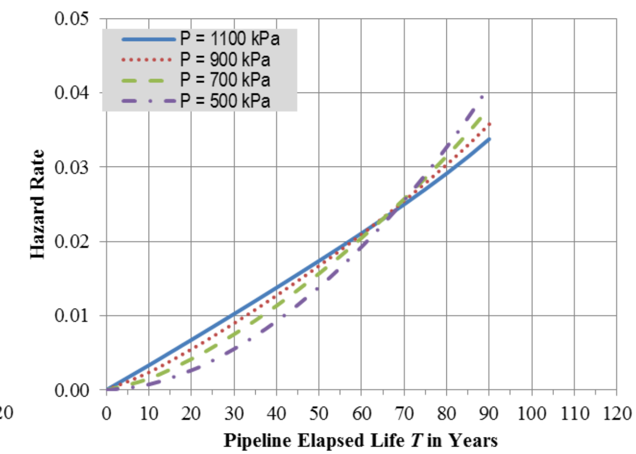
- Subjected to moderate corrosion
  r = 0.12 mm/year





- Subjected to strong corrosion
  r = 0.16 mm/year



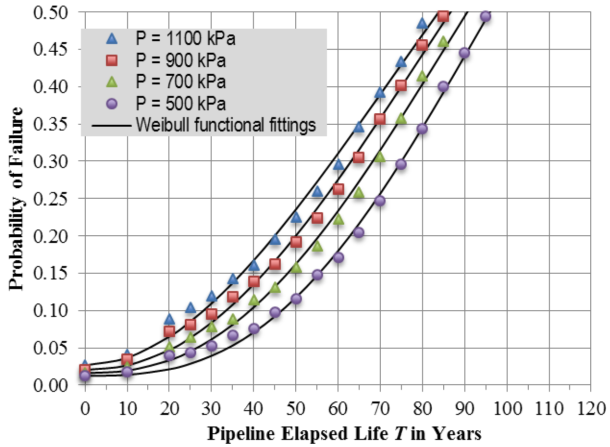


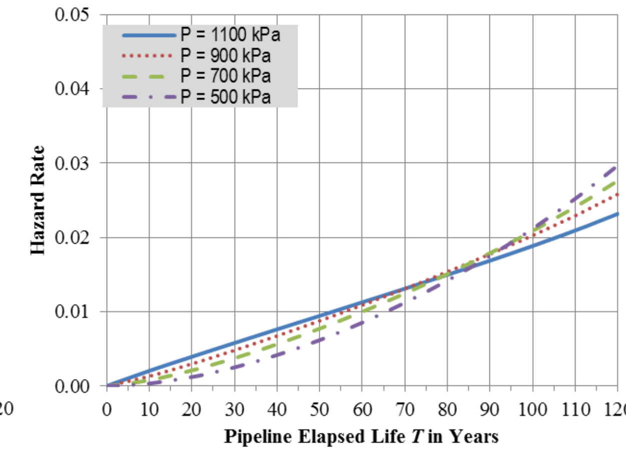
Comparison between pit and spun CI pipe cohorts (450 mm, Class C)

Some information need to refine:

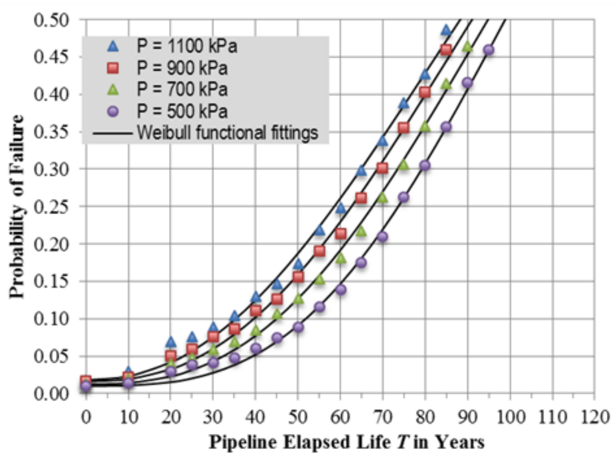
1) Pipe wall thickness
2) CI tensile strength
3) Lateral corrosion rates

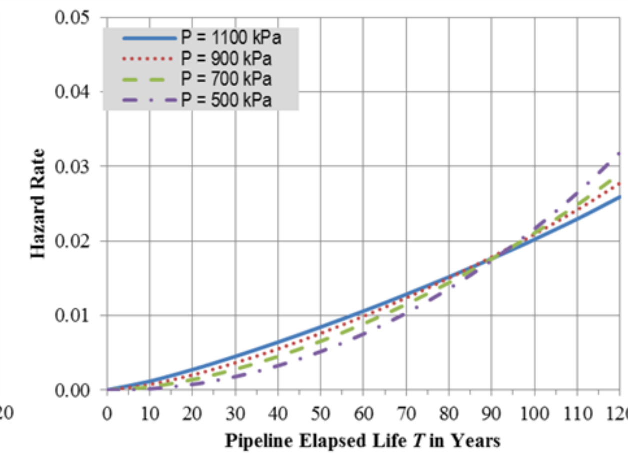
- Pit cast iron pipe Subjected to r = 0.12 mm/year





- Spun cast iron pipe Subjected to r = 0.12 mm/year





Part 4: Summary

Conclusions

- For large diameter pipe cohorts (D >= 300 mm), the initial of pipe failure (water leak) have been successfully studied using the probabilistic physical modelling technique (PPM). The lifetime failure probability, hazard rate were developed at specified cohort levels.
- The average water pressure is a significant factor. Higher operational pressure pipe cohorts have bigger failure rates at early servicing periods.
- Pipe tensile strength, lateral corrosion rates, wall thickness need to refined further for accuracy improvement.
- Corrosion rate is the most dominant factor influence the lifetime failure probability prediction.

Limitations and future work

- Corrosion patches are currently subject to circular shapes. The stress concentration factors tends to be under-estimated. Improvements will be made of the use of elliptical corrosion patches.
- Lateral corrosion rate is just assumed. More work is necessary urgently.
- Uniform corrosion rate is just assumed. More work is necessary urgently.
- The machine-learning approaches (e.g., the support-vector-machine) will be adopted to develop the limit state function of pipe failure.
- Spreadsheet models will be delivered to utilities, to analyze the failure data, and to estimate the time to failure probability.
- Updating the physical parameters are under investigation.