



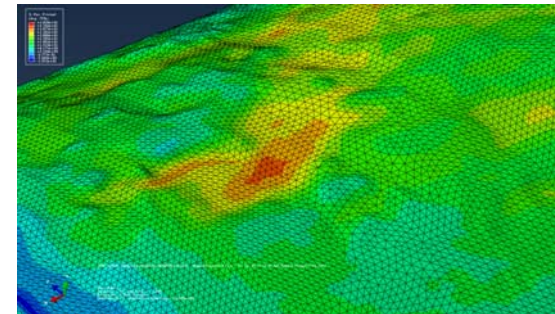
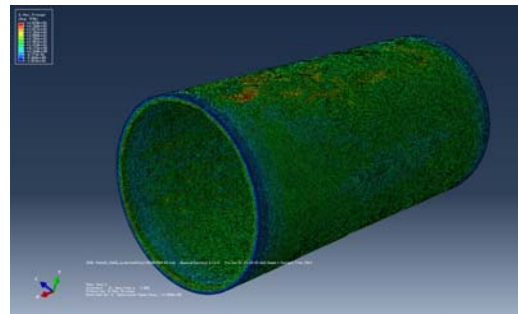
MONASH University

Engineering

Pipe Progress Presentation

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Dr. Jian Ji

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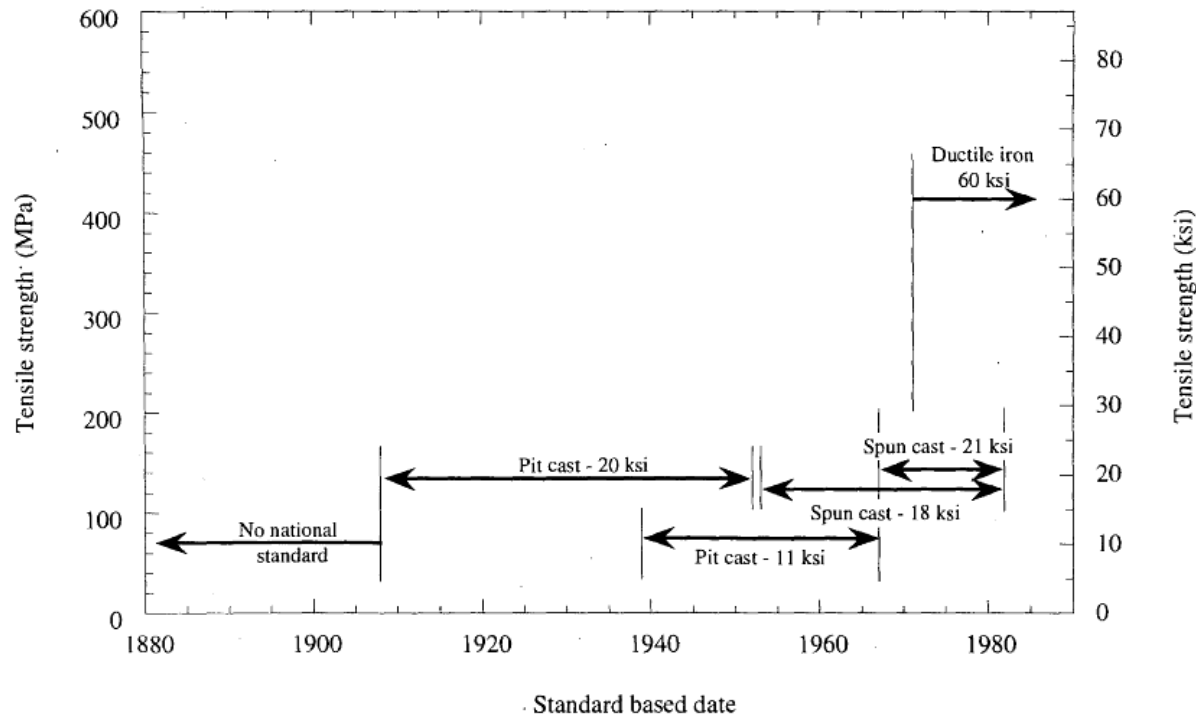


Cast Iron Large Diameter Pipes

Cast iron pipe failure mode

- Mechanical model and finite element method to study the crack (burst) of cast iron pipes.
- Leak before failure : there is a time lag between leak and burst, but we focus on the leak, which is acceptable for long-term failure prediction analysis.
- Limit state of leak before failure: maximum stress → tensile strength
- **Most contribution factors: corrosion, water pressure, tensile strength, wall thickness, pipe diameter.**

Timeline of design tensile strength (AWWA)



The design values of tensile strength is variable with their timeline. More test tensile strength values of Australia pipes are required.

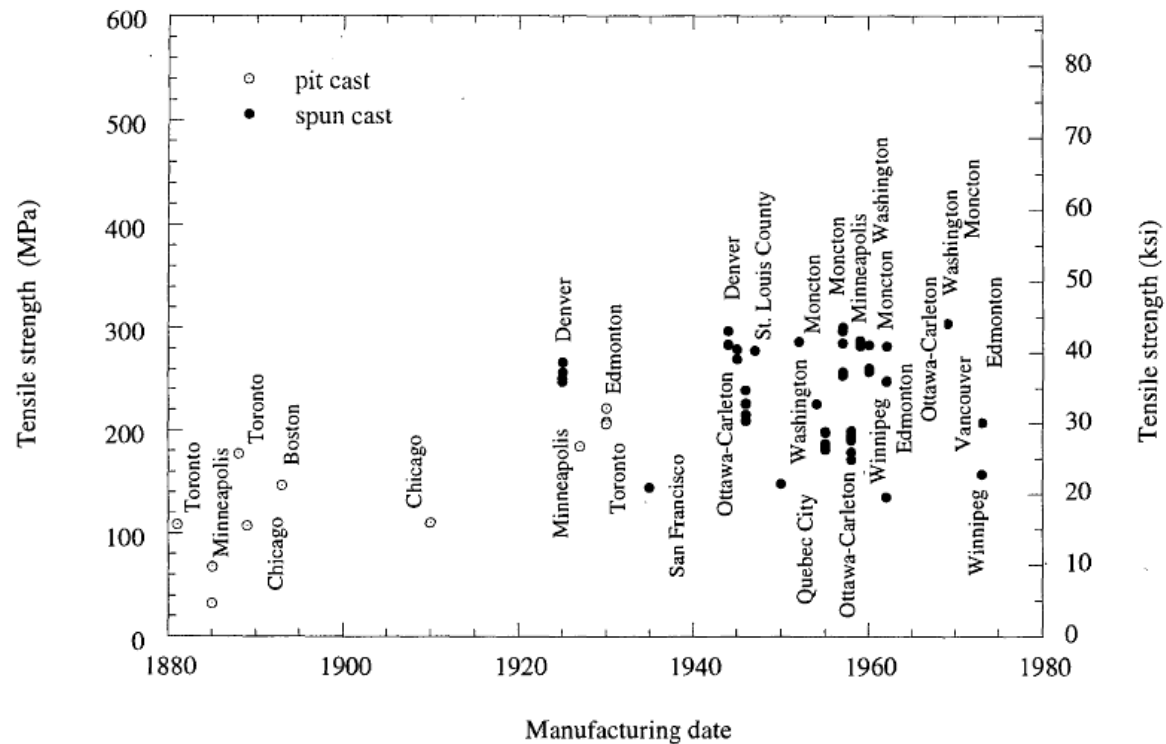
REFERENCE:

Rajani, B. Investigation of grey cast iron water mains to develop a methodology for estimating service life. American Water Works Association. 2000.

Design minimum tensile strength in Australia

	Pit Cast	Spun Cast	Reference
North Amer	76~214 MPa	124~276 MPa, 145~310 MPa	AWWA
Australia	139-154 MPa	170 MPa	British St., 1938; AIS, 1941
Monash test	103 MPa	140 MPa	

Corroded Specimen: tensile strength v.s. manufacture date

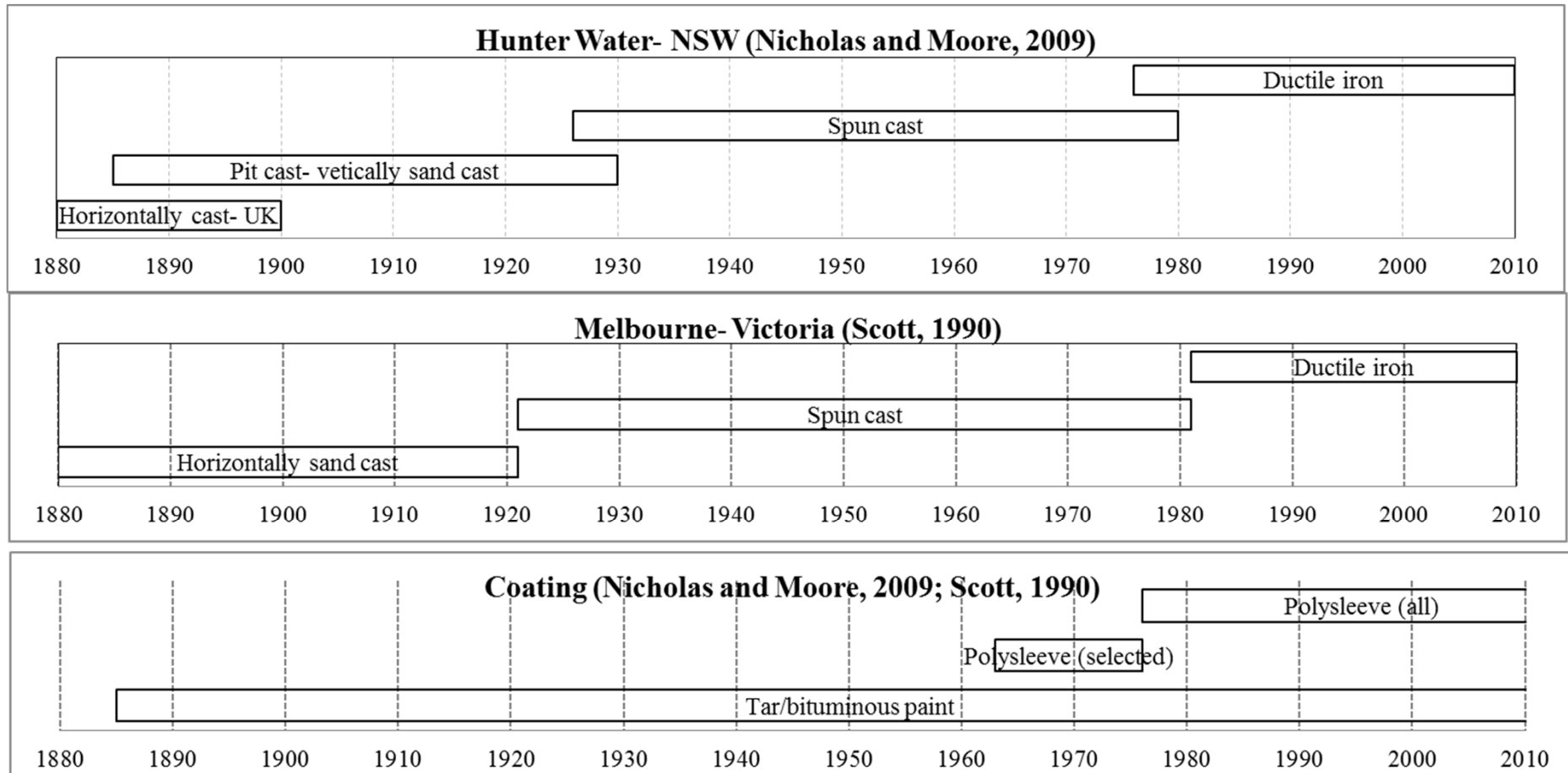


Significant variation of tensile strength can be observed for corroded specimen tests

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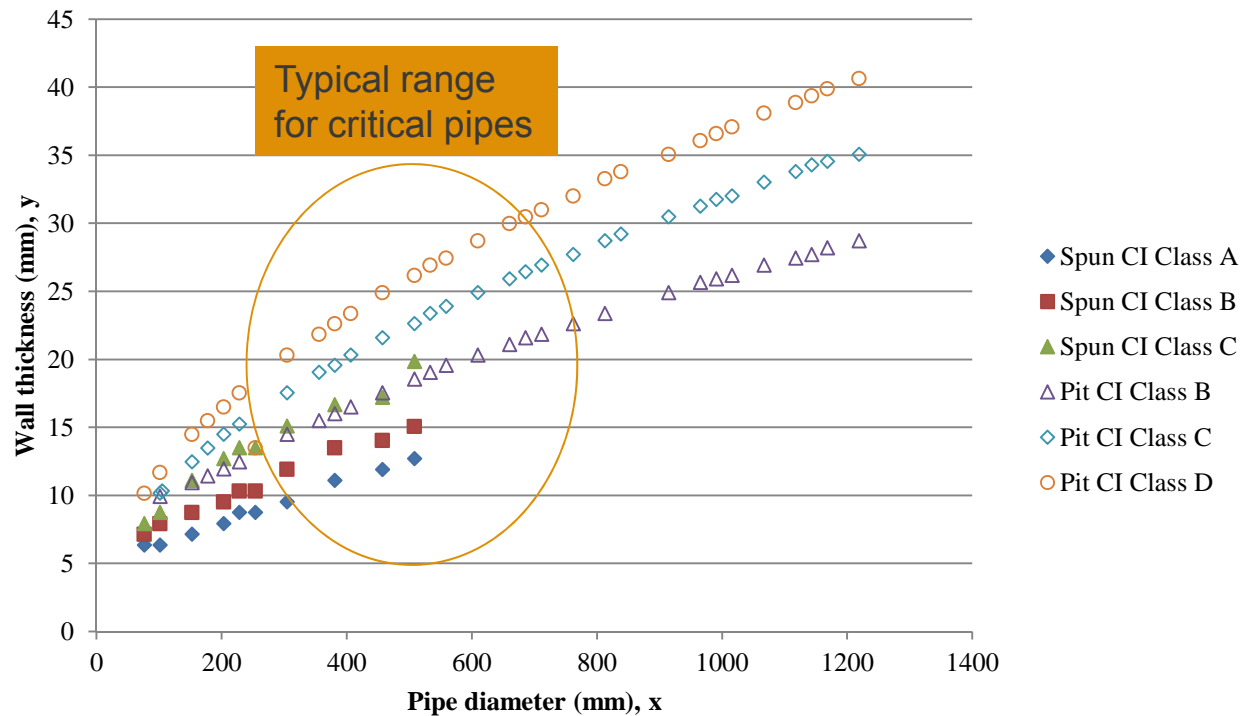
Rajani, B. Investigation of grey cast iron water mains to develop a methodology for estimating service life. American Water Works Association. 2000.

Australia Ferrous Piping Timeline



CI pipe thickness classification

- Spun cast iron pipe (AIS, 1941)
Pit cast iron pipe (British, 1938)



Categorizing of CI pipe cohorts

- To categorize the cohorts, the following parameters may be considered at first:
- Operational water pressure: 300 to 400; 400 to 500; 500 to 600; 600 to 700; 700 to 800; 800 to 900; 900 to 1000 kPa; etc.
- Cast iron material: pit cast iron, laid before 1925; spun cast iron, laid during 1930 to 1980; Mixed material type: laid between 1925 to 1930
- Typical pipe cohort diameter values are referred to the table below, they may include for example, 100, 150, 200, 300, 375, 450, 500, 600, 750 mm.
- Class of pipes according to the manufactured wall thickness

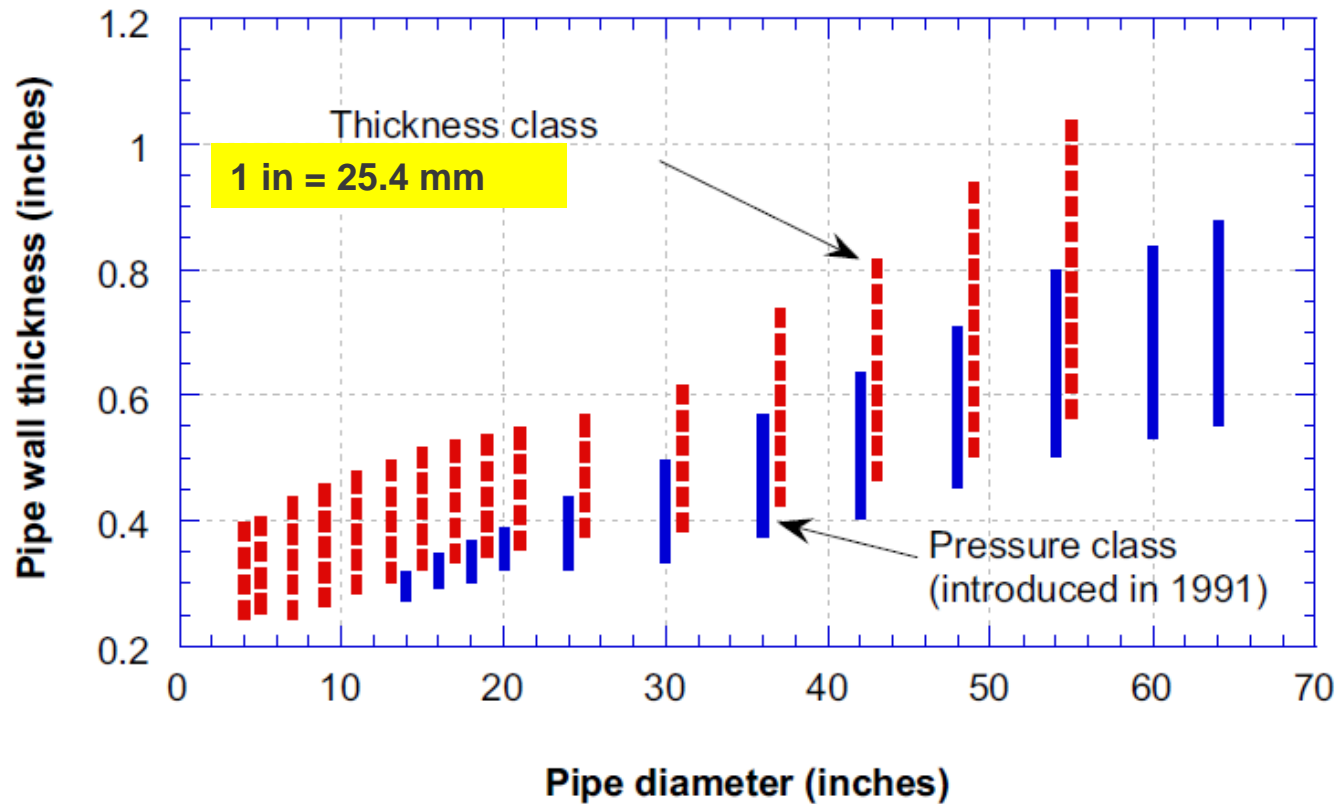


Ductile Iron Pipes

Ductile iron pipe failure modes

- Design minimum strength in tension
 - Approximately twice the strength of cast iron
 - North America:
 - Tensile: 60000psi = 414 MPa
 - Yield : 42000psi = 290 Mpa (U.S. PIPE AND FOUNDRY CO., 2013)
 - Australia:
 - Minimum tensile strength of 420 MPa (AS 2280)
- Mechanical failure (crack) is less common, the most majority is pitting corrosion (perforation), which can be repaired for continuous servicing.
- **Corrosion rate and wall thickness are the major contributions for pipe failure.**

North America: Range of DI pipe wall thickness (ANSI/AWWA C150/A21.5)



REFERENCE:
Rajani, B., Kleiner, Y., Kryz, D., Scientific, C. Long-term Performance of Ductile Iron Pipes. Water Research Foundation. 2011.

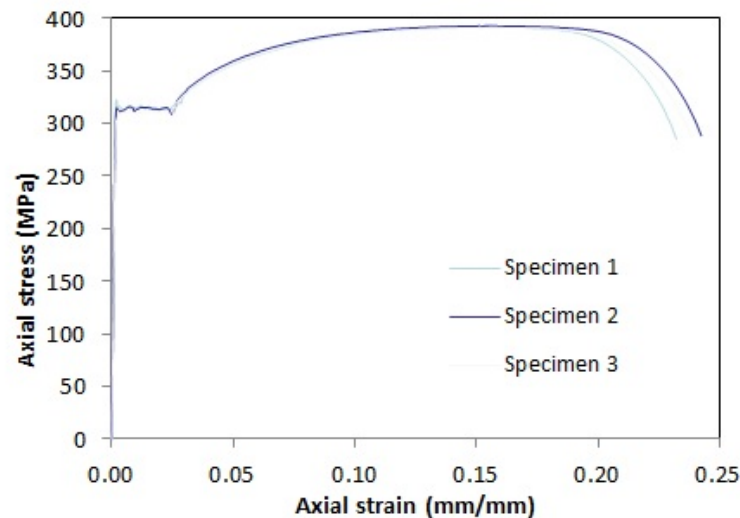
Australia: DI pipe wall thickness (AS/NZS 2280)

Nominal Size (DN)	Outside Diameter [mm (in)]	Nominal Wall Thickness [mm (in)]		Flange Class
		PN 20	PN 35	
100	122 (4.803)	-	5.0 (0.197)	7.0
150	177 (6.969)	-	5.0 (0.197)	8.0
200	232 (9.134)	-	5.0 (0.197)	8.0
225	259 (10.197)	5.0 (0.197)	5.2 (0.205)	9.0
250	286 (11.260)	5.0 (0.197)	5.6 (0.220)	9.0
300	345 (13.583)	5.0 (0.197)	6.3 (0.248)	10.0
375	426 (16.772)	5.1 (0.201)	7.3 (0.287)	10.0
450	507 (19.961)	5.6 (0.220)	8.3 (0.327)	11.0
500	560 (22.047)	6.0 (0.236)	9.0 (0.354)	12.0
600	667 (26.260)	6.8 (0.268)	10.3 (0.406)	13.0
750	826 (32.520)	7.9 (0.311)	12.2 (0.480)	15.0



Steel pipe tensile tests

Steel tensile tests



Steel pipe average properties	
Bulk density (g/cm ³)	6.2
Peak load (kN)	31.0
Peak stress (MPa)	392
Young's modulus from gauge strain (MPa)	200.5
Average Poisson's ratio	0.29
Upper yield strength (MPa)	317
Lower yield strength (MPa)	308
Yield point elongation (%)	2.5
Uniform elongation (%)	15.7
Elongation at failure (%)	23.8
Secant Modulus (GPa)	65.7



Back-figure Physical Parameters Using Bayesian Approach *Theoretical development*

A systematic analysis to combine our physical models
with observed failure data

Mechanical model: patch stress analysis for pipe barrel

- 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:

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

- For observed failure pipes, the limit state function is 0 in theory:

$$g(\mathbf{x}, t) = 0$$

Model error in pipe failure prediction

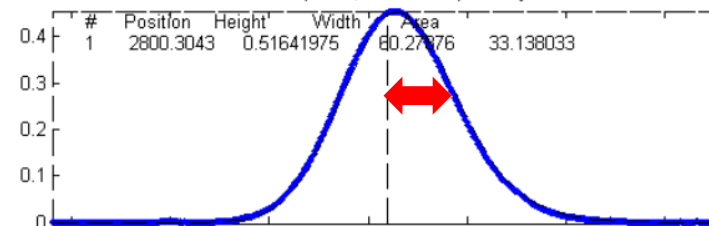
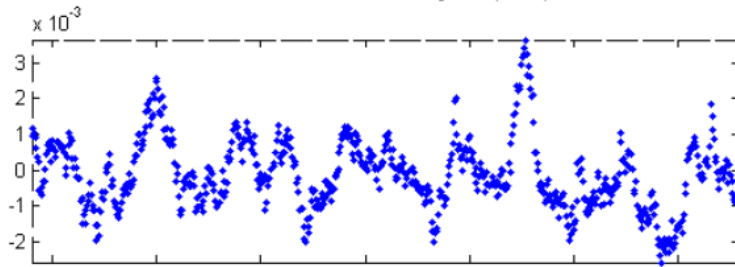
- Let $\tilde{y}(t)$ be the true value of the time-dependent response $y(t)$ of a mechanical system. Suppose we have a mechanical model \mathcal{M} that can perfectly predict the response to inputs $\tilde{\mathbf{x}}$ at time t .

$$\tilde{y}(t) = \mathcal{M}(\tilde{\mathbf{x}}, t)$$

- In practice, there is no perfection, and errors arise between the modelling result and field measurement or observation

$$\mathcal{M}(\tilde{\mathbf{x}}, t) = y_{mes}(t) + e$$

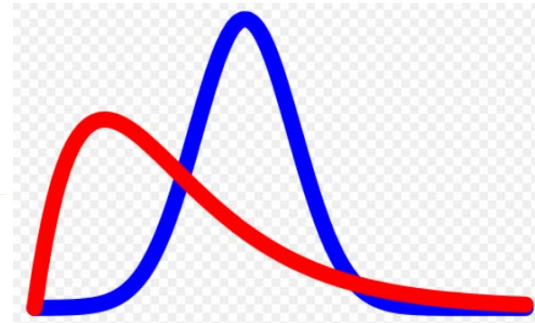
- Key: Suppose the observation error $e = y_{mes}(t) - \mathcal{M}(\tilde{\mathbf{x}}, t)$ is a zero-mean Gaussian random realization, with a standard deviation σ_e .



Basic physical parameters and prior knowledge

- Water pressure
- Corrosion rate
- CI tensile strength
- Wall thickness
- Patch lateral corrosion size

Subject to statistical distribution



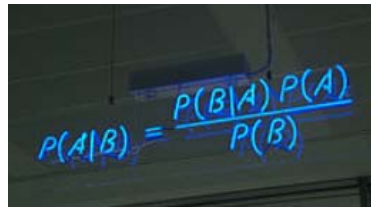
Statistical back analysis of physical parameters

- Objective
 - Use observed pipe failures to update our knowledge of the a priori assumption of some important physical parameters (uncertainty)
- Procedure for Bayesian Inverse Analysis
 - Basic a priori statistical distribution of inputs (physical parameter)
 - Mechanical model predicting the output using the inputs samples
 - Observed outputs
 - Bayesian updating by MCMC

Bayesian inverse analysis

- Bayes' Theorem

A simple introduction in Wikipedia



A photograph of a chalkboard with the formula for Bayes' Theorem written in blue chalk: $P(A|B) = \frac{P(B|A)P(A)}{P(B)}$.

- Bayes' Theorem: the posterior PDF depends on the prior PDF and likelihood

$$f_{\mathbf{X}}(\tilde{\mathbf{x}} | y_j) \equiv f_{\mathbf{X}}(\tilde{\mathbf{x}}) = c p_{\mathbf{X}}(\tilde{\mathbf{x}}) L(y_j | \tilde{\mathbf{x}})$$

- Likelihood function for indirect Bayesian updating

$$L(y_1, \dots, y_N | \tilde{\mathbf{x}}) \propto \prod_{j=1}^N \frac{1}{\sigma} \exp \left[-\frac{1}{2} \frac{(y_j - \mathcal{M}(\tilde{\mathbf{x}}, t_j))^2}{\sigma^2} \right]$$

- Markov Chain Monte Carlo (MCMC) to simulate the Posterior PDF
 - Metropolis-Hastings Algorithm


A proposal distribution, like Normal

$$x_{i+1} = \begin{cases} \tilde{x} \sim q(x | x_i) & \text{with probability } \alpha(x_i, \tilde{x}) \\ x_i & \text{else} \end{cases}$$

Acceptance probability

$$\alpha(x_i, \tilde{x}) = \min \left\{ 1, \frac{f_X(\tilde{x}) q(x_i | \tilde{x})}{f_X(x_i) q(\tilde{x} | x_i)} \right\}$$

$$\alpha(x_i, \tilde{x}) = \min \left\{ 1, \frac{f_X(\tilde{x})}{f_X(x_i)} \right\}$$

- 
- High-dimensional MCMC sampler
 - Metropolis within Gibbs: sampling variables one by one, each with a metropolis trick.
 - Casacaded Metropolis Sampling: first examine the prior acceptance ratio, then examine the likelihood acceptance ratio (Tarantola 2005).

Selective Results for SW:



Cohort 300 Spun Cast Iron

Cohort 375 Spun Cast Iron

Cohort 450 Spun Cast Iron

Cohort 500 Spun Cast Iron

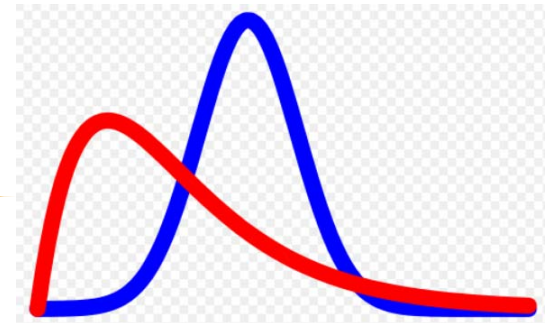
- Assumption:
 - SCF model and stress model are good enough, with prediction error for LSS = 0.2, i.e., 70% prediction lies between 130 ± 26
 - Assume the time to first failure of each pipe segment.

Basic physical parameters and prior knowledge

- Parameters with uncertainty and to be back figured
 - Water pressure YES
 - Corrosion rate YES
 - CI tensile strength YES
 - Wall thickness, cohorted
 - Patch lateral corrosion size Yes in next TAC
- Prior Assumption

Lognormal distribution, to avoid negative physical parameter

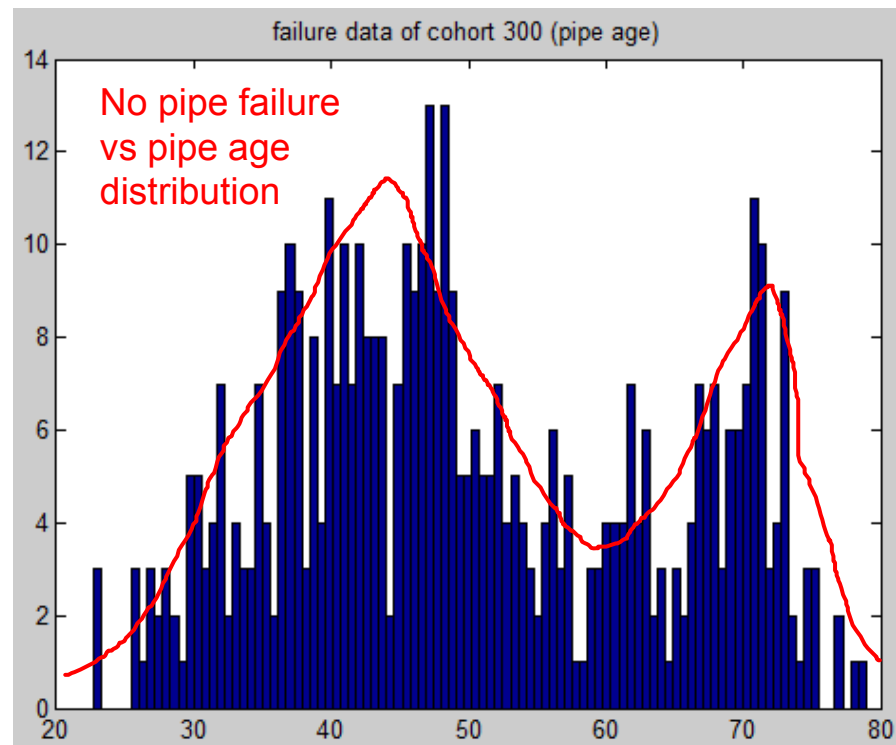
Subject to statistical distribution



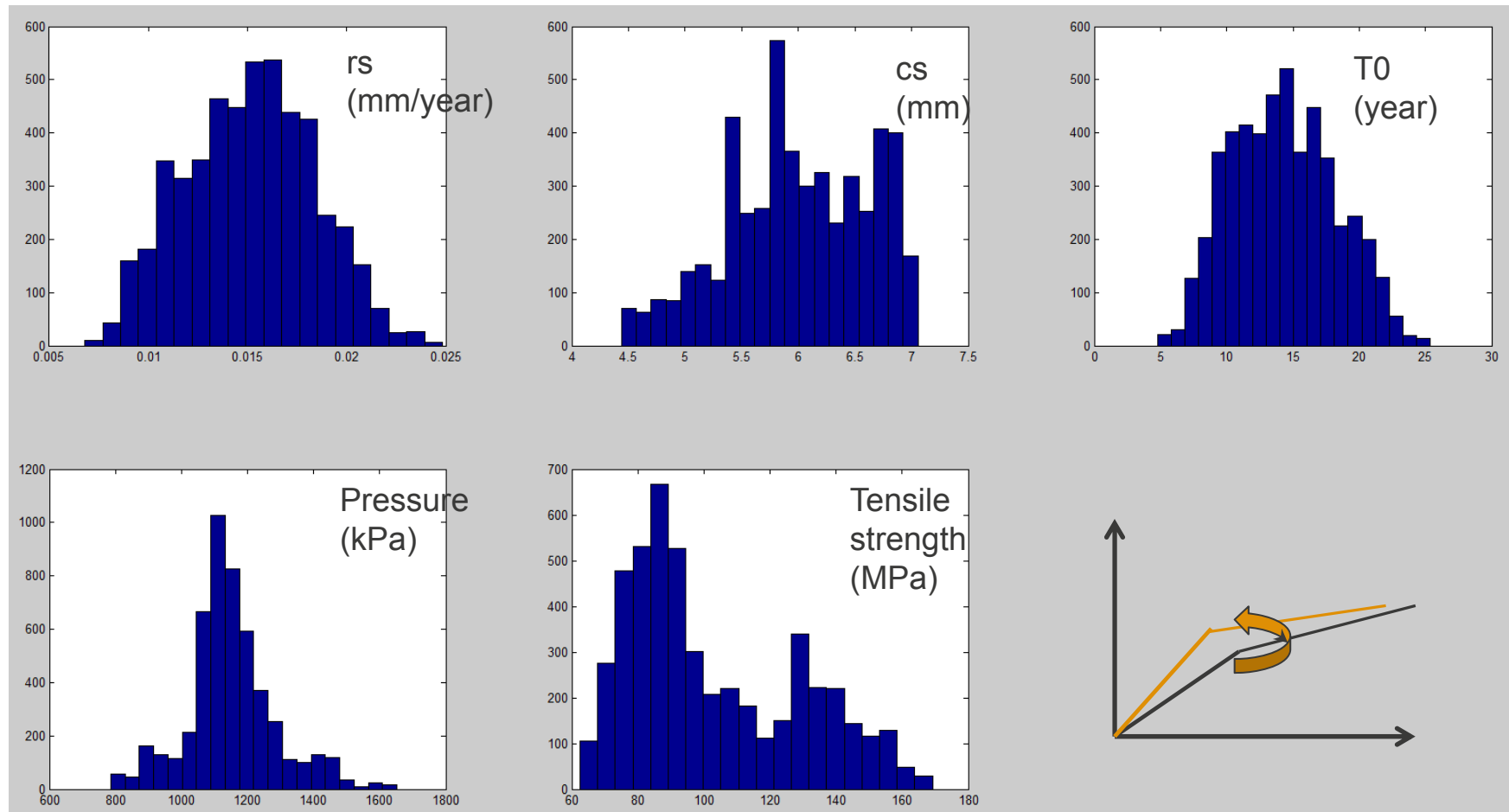
Failure data: Cohort 300 Spun Cast Iron (after 1930s)



- There are 474 failure pipes for the cohort 300mm, recorded between 2001 to 2012
- Multiple failure mode shown by the data.
- Limitation: data is not fully recorded from the beginning.
- Records of early failure data shall be necessary



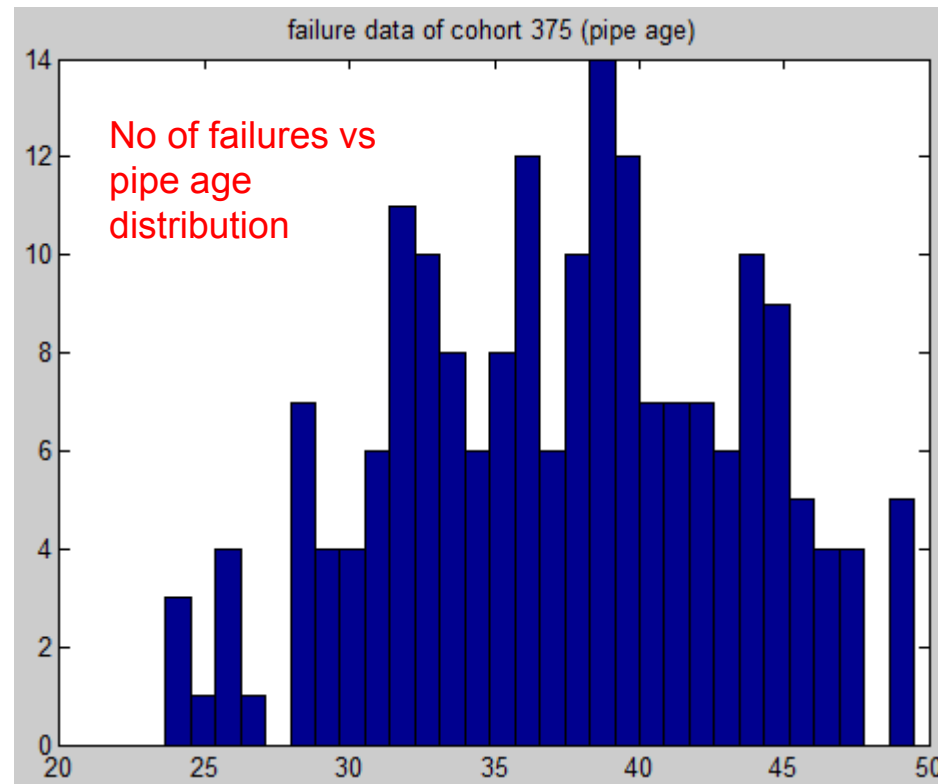
Back-figured Physical Parameters



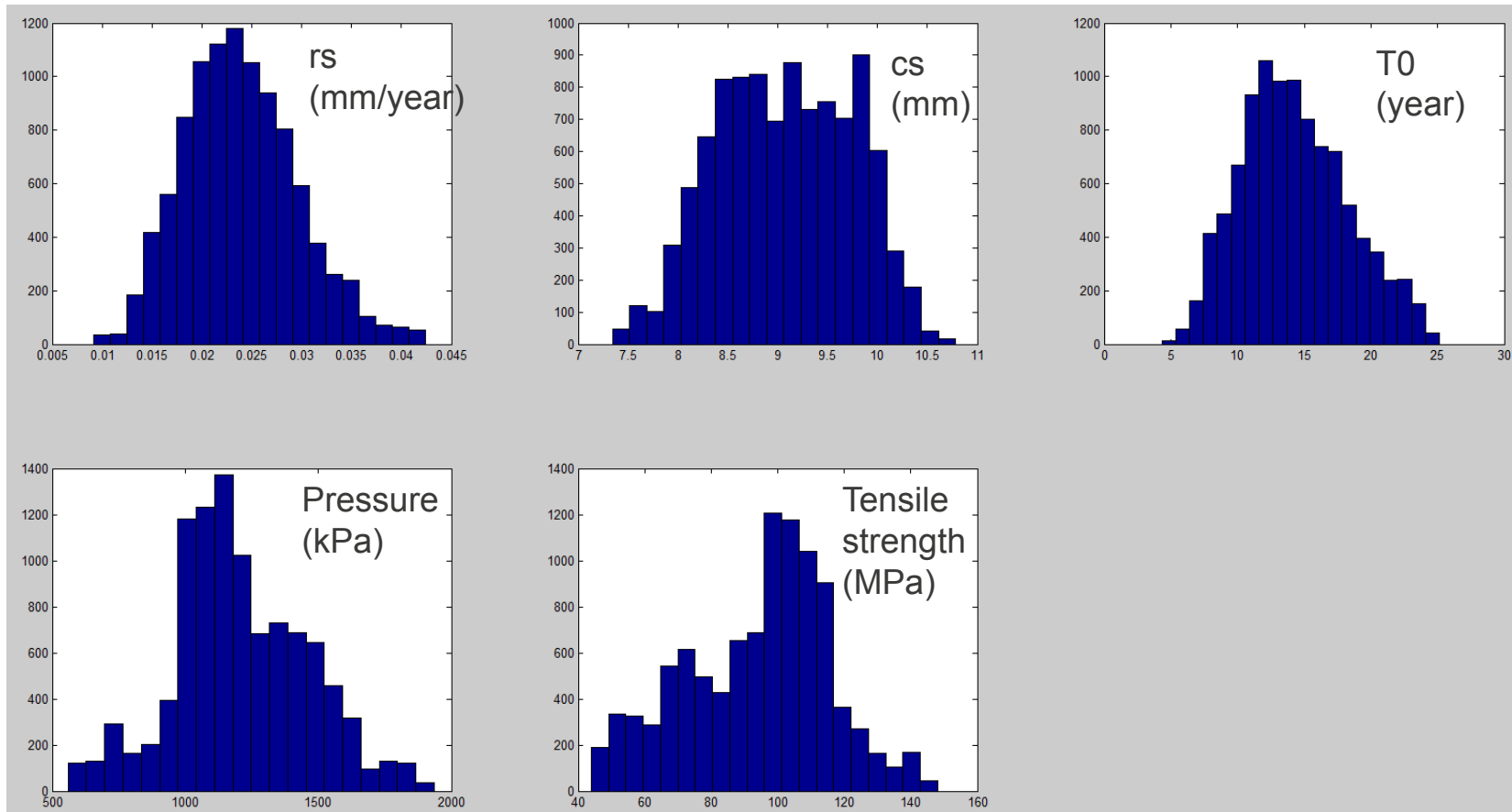
Failure data: Cohort 375 Spun Cast Iron



- Installed after 1960s, 191 cohort failure data

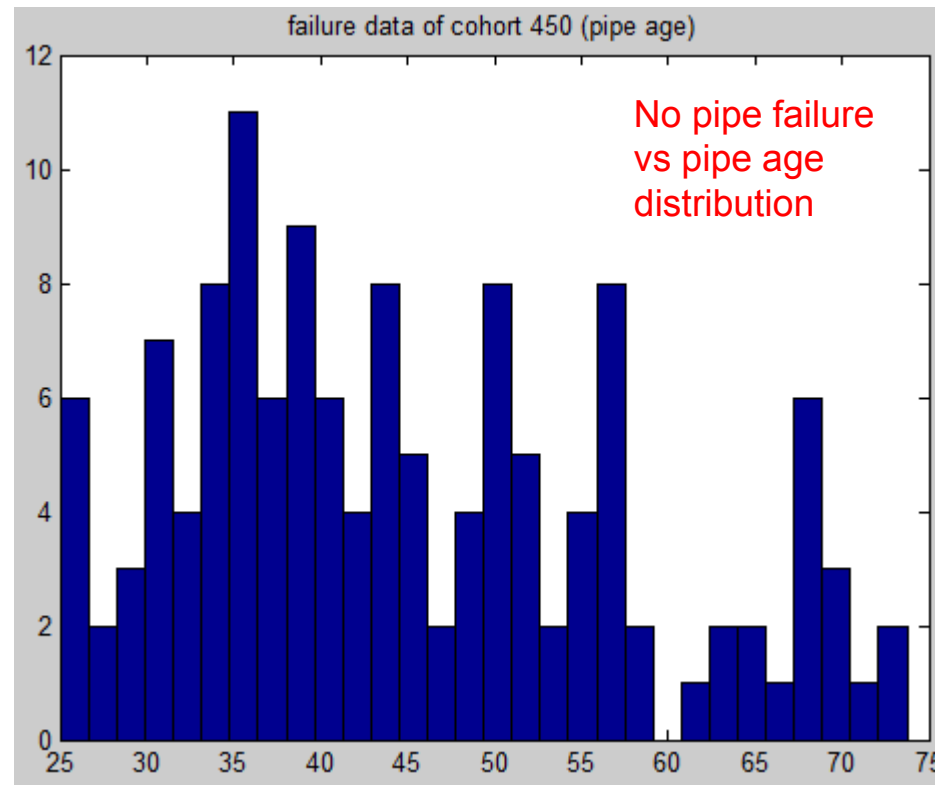


Back-figured Physical Parameters

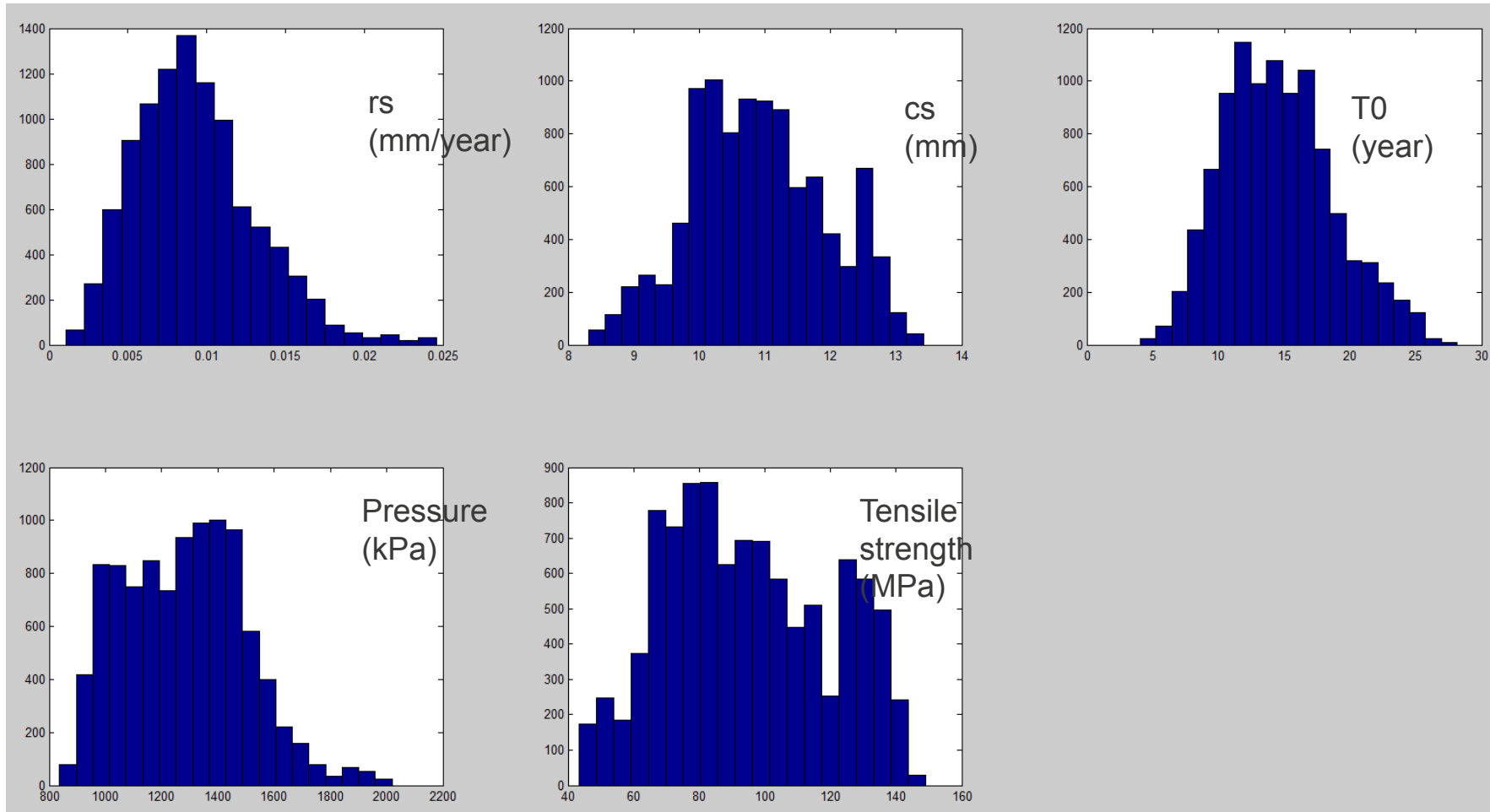


Failure data: Cohort 450 Spun Cast Iron

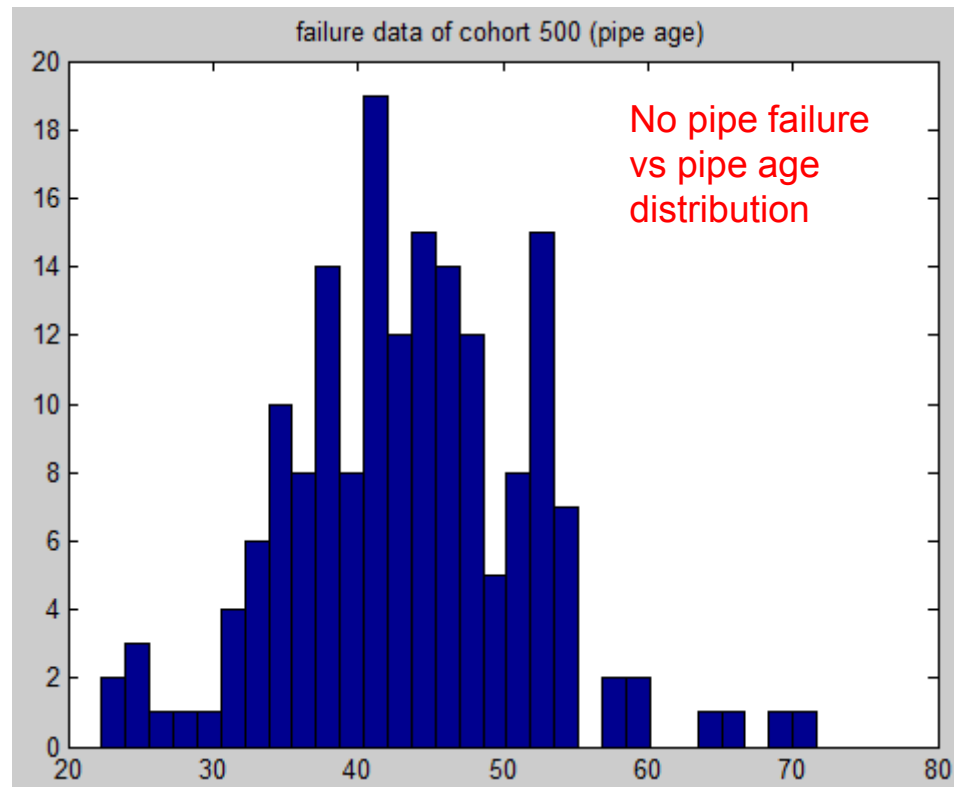
- Installed after 1960s, 132 cohort failure data



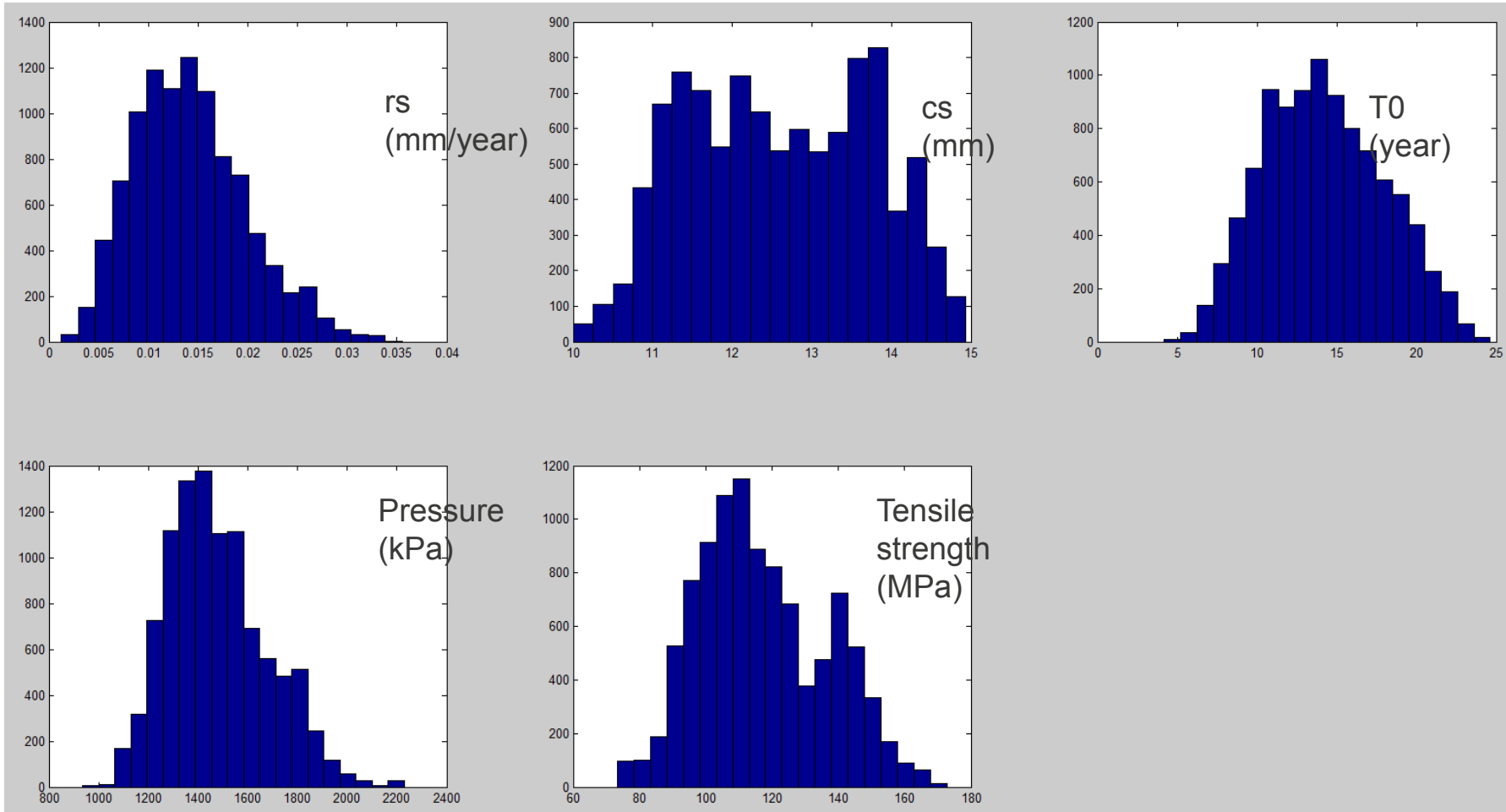
Back-figured Physical Parameters



Failure data: Cohort 500 Spun Cast Iron



Back-figured Physical Parameters

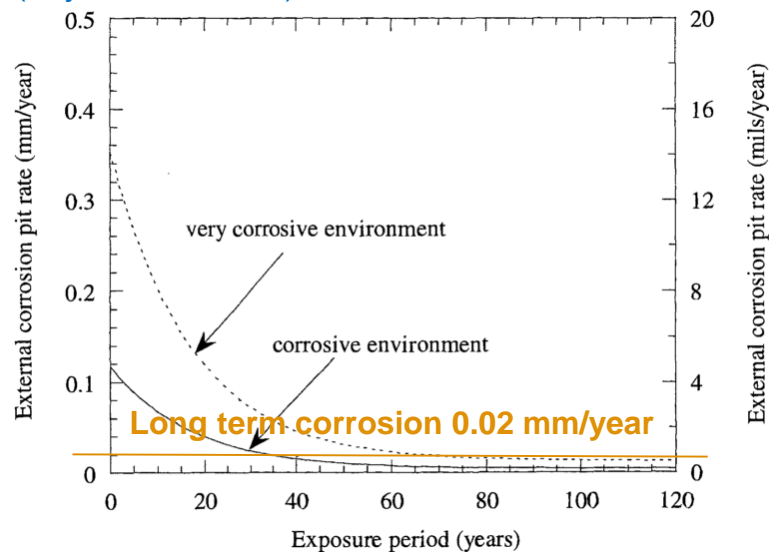


Comparison between prior and posterior mean values

- Prior, assumptions
 - Corrosion
 - $r_s = 0.05$ to 0.12 mm/year
 - $cs = 3$ to 6 mm
 - Water pressure
 - 500 to 1000 kPa
 - Tensile strength
 - 100 to 130 kPa
- Posterior, back figured
 - Corrosion
 - $r_s = 0.01$ to 0.02 mm/year
 - $cs = 7$ to 11 mm
 - Water pressure
 - 1100 to 1500 kPa
 - Tensile strength
 - 70 to 100 kPa

Typical long-term corrosion rates for ferrous pipes

Long-term corrosion rate for grey cast iron pipes (Rajani et al., 2000)



In this study, the back figured rs is between 0.01 to 0.02 mm/year, indicating very low to low long-term corrosion,

Need more work and data for calibration

Long-term corrosion rate for ductile iron pipes, reported in North America (Rajani et al., 2011)

Soil corrosivity	Corrosion parameters for two-phase model			
	Minimum corrosion rate, a (mm/year)	k (mm)	c (1/year)	Maximum corrosion rate, $a + kc$ (mm/year)
Very low (VLC)	0.0042	1.95	0.058	0.1173
Low (LC)	0.0210	9.75	0.058	0.5865
Moderate (MC)	0.0252	11.70	0.058	0.7038
High (HC)	0.0294	13.65	0.058	0.8211
Very high (VHC)	0.0336	15.60	0.058	0.9384

REFERENCE:

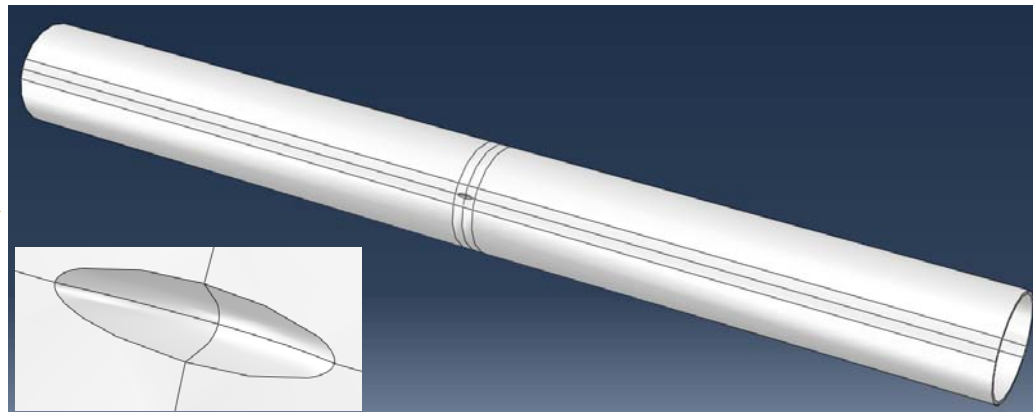
- Rajani, B. Investigation of grey cast iron water mains to develop a methodology for estimating service life. American Water Works Association. 2000.
- Rajani, B., Kleiner, Y., Krys, D., Scientific, C. Long-term Performance of Ductile Iron Pipes. Water Research Foundation. 2011.

Conclusions

- Based on the mechanical models (stress, corrosion patch SCF, etc.), the corrosion rate parameters are back-analyzed to conform to cohort failure data. When the bilinear corrosion model is adopted, the corrosion interception c_s value tends to be a higher value which is commonly around $2/3$ of the pipe wall thickness. In contrast, the long-term corrosion rate r_s tends to be small, typically around 0.01 to 0.02 mm/year, on average. This finding indicates that corrosion patches develop rapidly in the initial stage, and slowly progressed for long-term.
- The water pressure yielding leakage on the corrosion patch increases with the pipe diameter. Their mean values have shown to be more than 1100 kPa for all the cohorts analyzed. This usually refers to the maximum water pressure, i.e., steady state + transient.

- On average, the back-figured tensile strengths tend to be very low value, which is less than 100 kPa, for spun cast iron pipes. This is not very common as observed from our lab test. More research is needed to investigate this difference.
- So far, the back-analysis is based on circular patch assumptions. With the progressively improved elliptical patch models developed, we will show more improved numerical results in the next TAC.

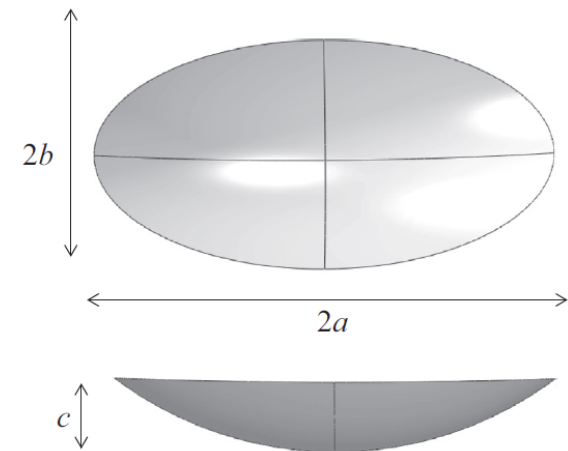
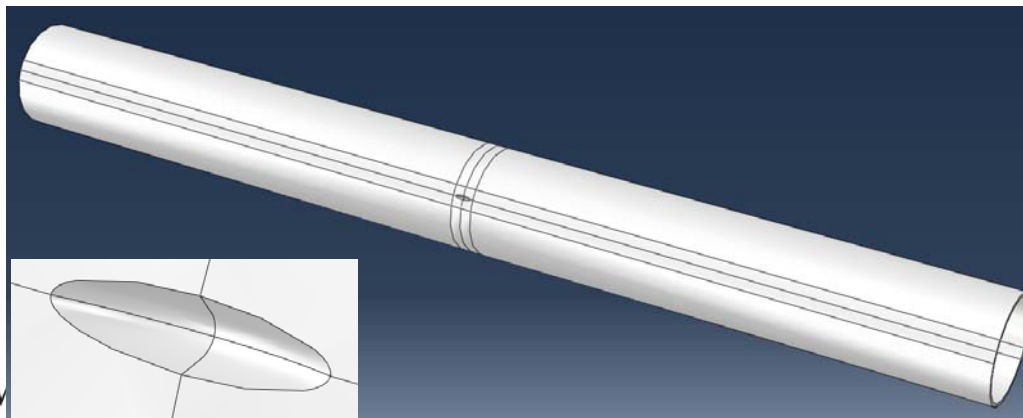
Elliptical corrosion patches to be considered in probabilistic analysis



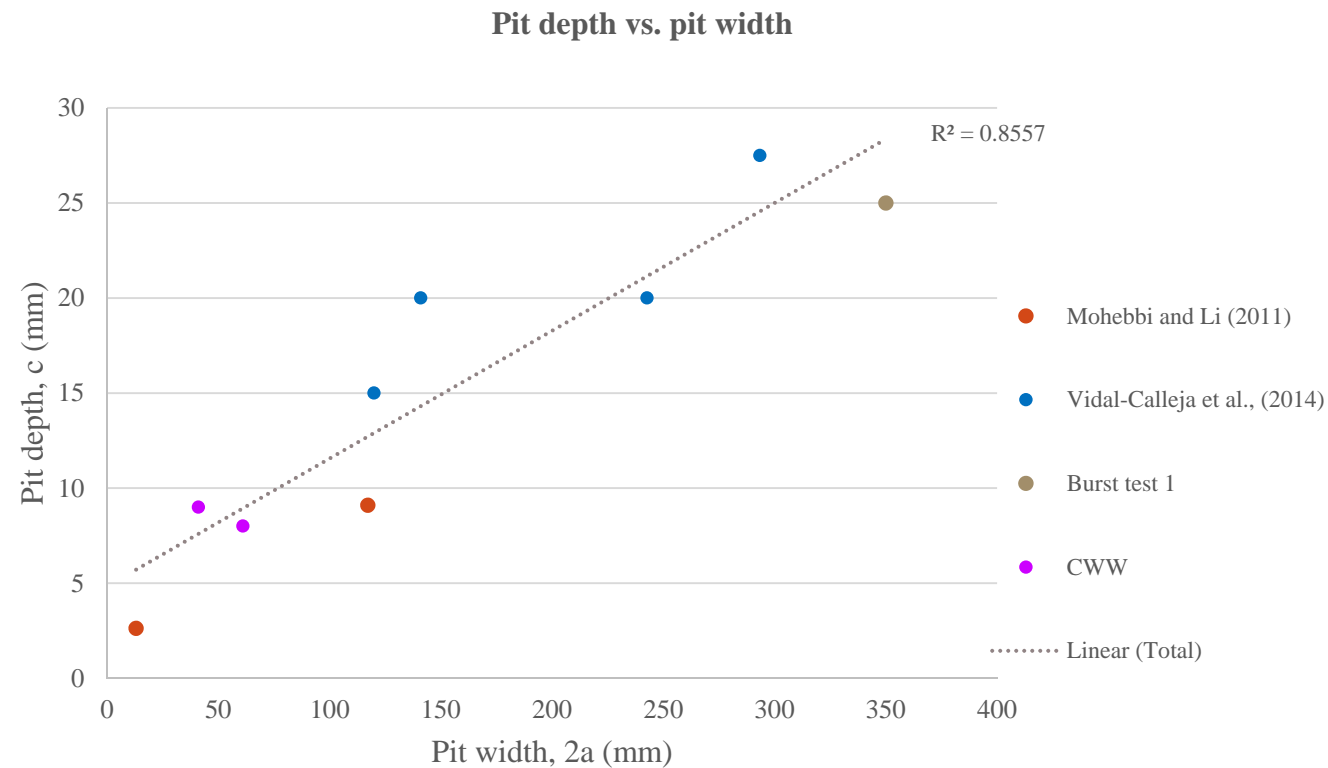
Basic considerations for elliptical corrosion patch

- Corrosion pitting area is a critical factor of corrosion configuration in terms of reducing piping integrity and bursting strength.
- Limited data were reported in previous research (Mohebbi and Li, 2011).
- Ratio of corrosion patch length in longitudinal direction to maximum pitting depth is proposed:

$$\text{Ratio} = 2a / c$$



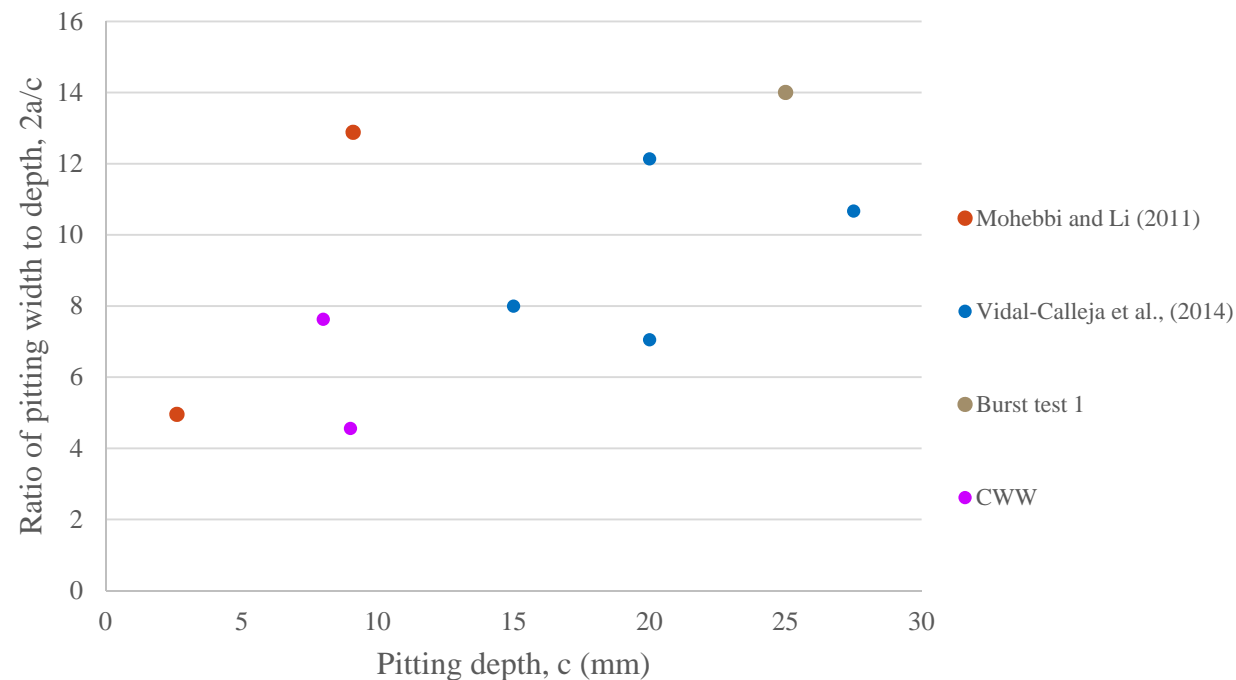
Correlation between patch depth and width



There is a correlation between pitting depth and pitting width for cast iron pipes.

Ratio of patch lateral size to corrosion depth

Pit depth vs. ratios of pitting width to depth



The cases of general (uniform) corrosion and coalescent patches were not included in this preliminary result.

Ratios range from 4.5 to 14 were observed, and more efforts required in data collecting.



Expected outcome for Next TAC

- Use the elliptical corrosion patch SCF model to improve the back figuring
- Use the back figured parameters to enhance the predictions
- Need more failure data for our analysis



Thank You