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Corrosion modelling Activity 3

Robert Petersen

Rob Melchers

Outline

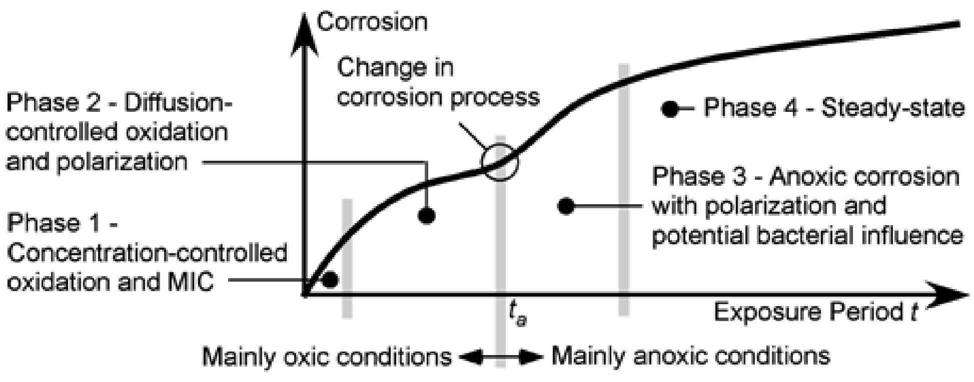
- Aim
- Background
- Modelling approach
- Current corrosion model
- Other effects - outliers
- Discussion
- Future work

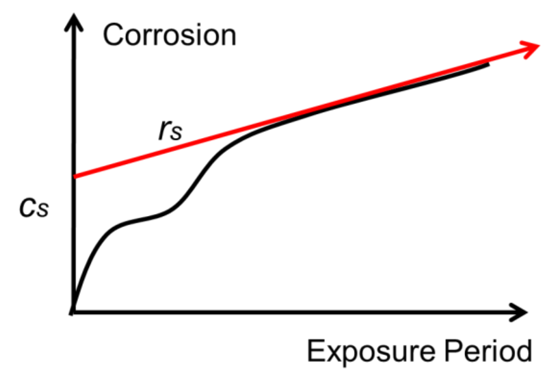
Aim – activity 3

- Develop a (science-based) model for external corrosion depth as a function of time and soil environment
- Calibrate model to actual field data
- Older, large diameter cast iron cement lined pipes

Background

- Long-term corrosion in soils
- Follows bi-modal model (draft CS paper available)
- Approach - calibrate model to *real field data*
- Corrosion loss is a function of time and soil parameters





Background 2

- Long-term trend = basis for model
- Only consider effect of variables on long-term trend
- Variables identified from

  (i) understanding of conventional atmospheric corrosion

  (ii) understanding of microbiological corrosion (never before specifically considered in soil corrosion models)

- Simple view: The soil just fills up part of the space and may change the properties of the soil water.

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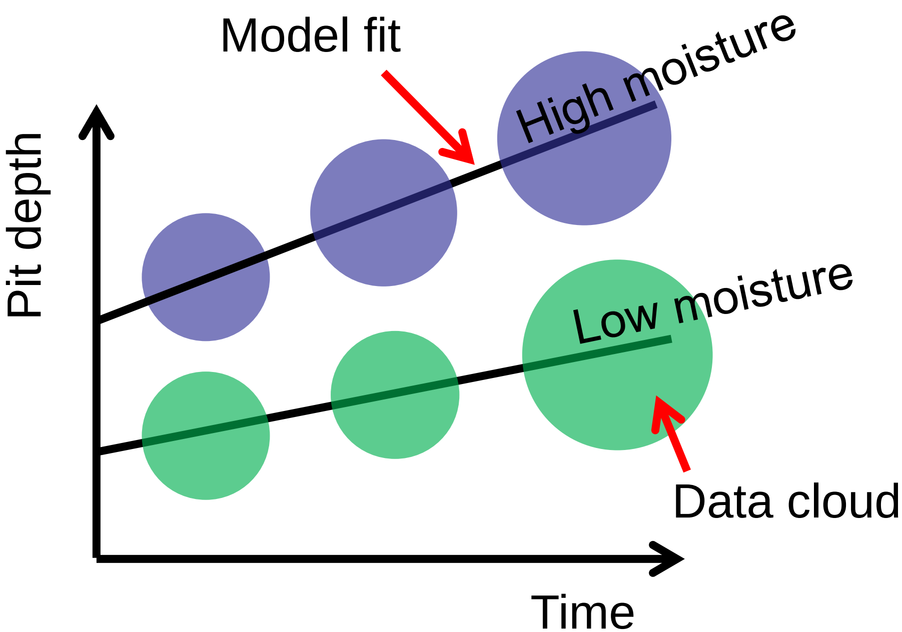
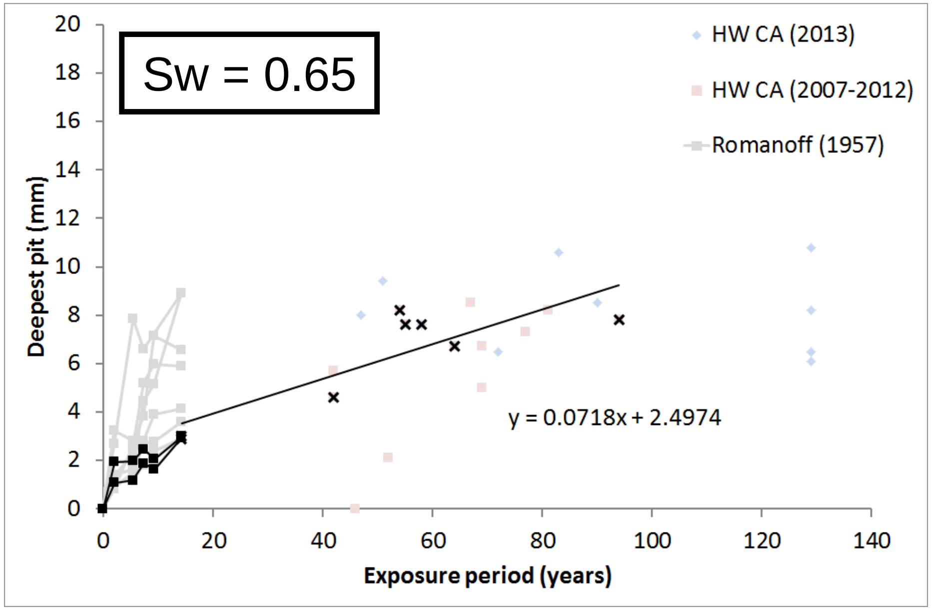
Background 3

- Moisture content is important for corrosion loss
- Not given in Romanoff or other sources...





Concept

Actual

Modelling approach

- Modelling process:
- Identified parameters influencing growth of pits
- Based on corrosion in other environments
- Reviewed existing literature (e.g. Romanoff 1957 report)
- Data available considered insufficient
- New data protocol developed, implemented
- Collected new, more comprehensive data from:
  - 1. Hunter Water field trials
  - 2. SW breaks
  - 3. SW Test bed
  - 4. Perth WC CA.

Factor.	Likely effect on long-term corrosion*.	Importance
Soil moisture content.	Essential for corrosion to occur. Higher moisture content increases r.	High
Nutrients in soil water:		
Organic carbon	Essential for MIC.	High
(Dissolved) Inorganic nitrogen (DIN)	Higher DIN tends to increase MIC in marine conditions.	High
Sulphates	Higher sulphate concentration tends to increase MIC. No significant effect for abiotic corrosion.	High
(Dissolved) Inorganic Phosphorus	Necessary nutrient for MIC.	High
Chlorides in soil water	Chlorides increase pit depth in immersion corrosion.	High
Phosphates in soil water	Known inhibitor for initiation of abiotic corrosion	High
Carbonate hardness of soil water	Known to reduce long-term marine corrosion. Decreases permeability of rusts.	High
Soil pH	No effect on immersion corrosion rate for normal range of soil pH.	Low
Soil temperature (mean, range)	Higher temperatures increase corrosion.	High
Soil permeability:		
Porosity	Increased porosity permits more moisture to contact pipe. Also may affect rates of diffusing species close to pipe wall.	High
Compaction	Higher compaction likely to reduce permeability	Low
Clay content	Higher tends to reduce permeability	Low
Pipe depth	No known direct effect for normal conditions	Low
Soil resistivity	Indirect measure of other influencing factors	Low

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Modelling approach 2

- Simplifications for SW & HW data sets
- Ignore temperature – all in same geographical area
- Assume organic carbon, sulphates sufficient for MIC
- pH similar in all soils
- Ignore permeability – assume *similar* backfill practices
- Assume good backfill ...
- Depth of pipe not relevant

- Resistivity, LPR etc. etc. are derived tools/measurements

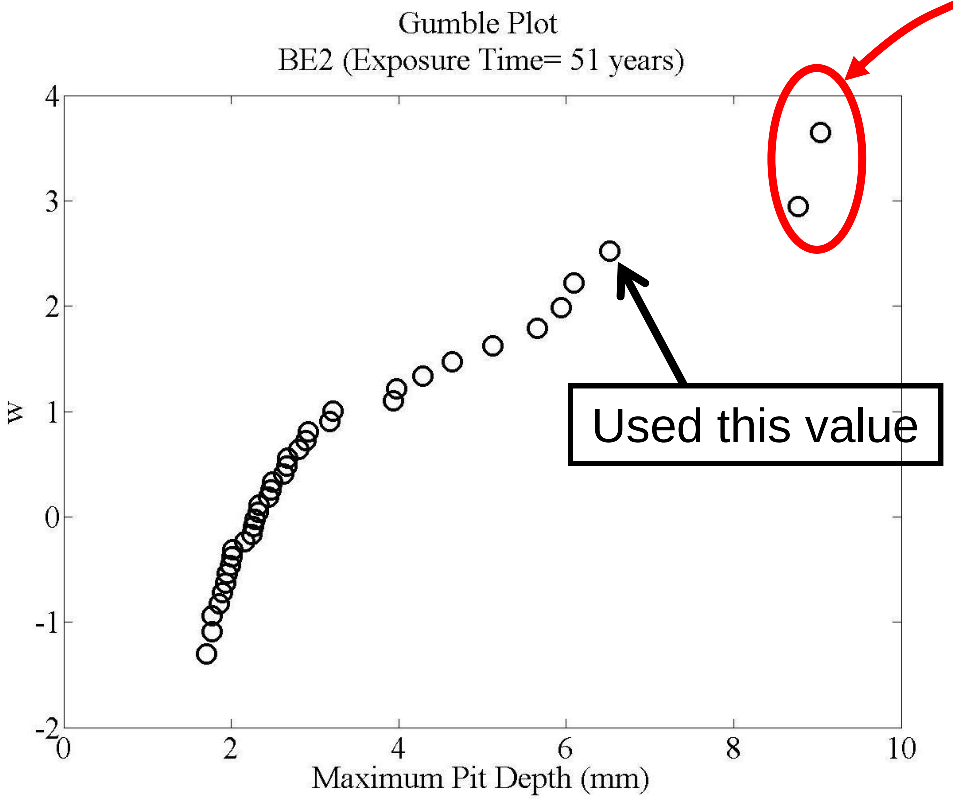
Summary of data – part – 37 cases

Table 2. Soil parameters and corrosion penetration observed for buried cast iron pipes.

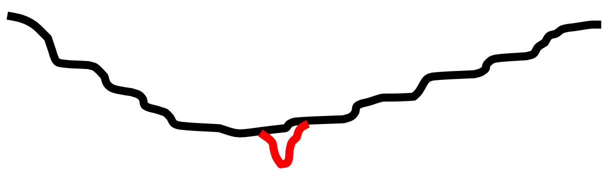
	Site	Pipe type [a]	Exposure period (years) [b]	Soil backfill type	Soil pH	Moisture content (% g/g moist soil)	Nitrate (mg/kg)	Chloride (mg/kg)	Phosphate (mg/kg)	Observed maximum penetration p_0 (mm) [c]
	Column No.	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Set 1									
1	BO2	YS	34	clay		12.6	0.9	180	0.11	7 [b]
2	RT1	YS	36	sand		17.8	0.6	10	2.9	1.7
3	RT2	YS	36	sand		14.8	<0.3	50	0.9	3.8
4	BE7	YS	43	sand		4.5	0	30	0.07	1.4
5	MC4	YS	46	clay		24.9	0	60	0.43	4.7 [b]
6	DU2	YS	47	clay		20.9	2.2	160	0.18	8
7	BE2	SD	51	clay		25	0.6	120	0.03	6.5 [b]
8	BE5	SD	51	clay		18.1	1.9	310	0.02	6 [b]

Modelling approach 4

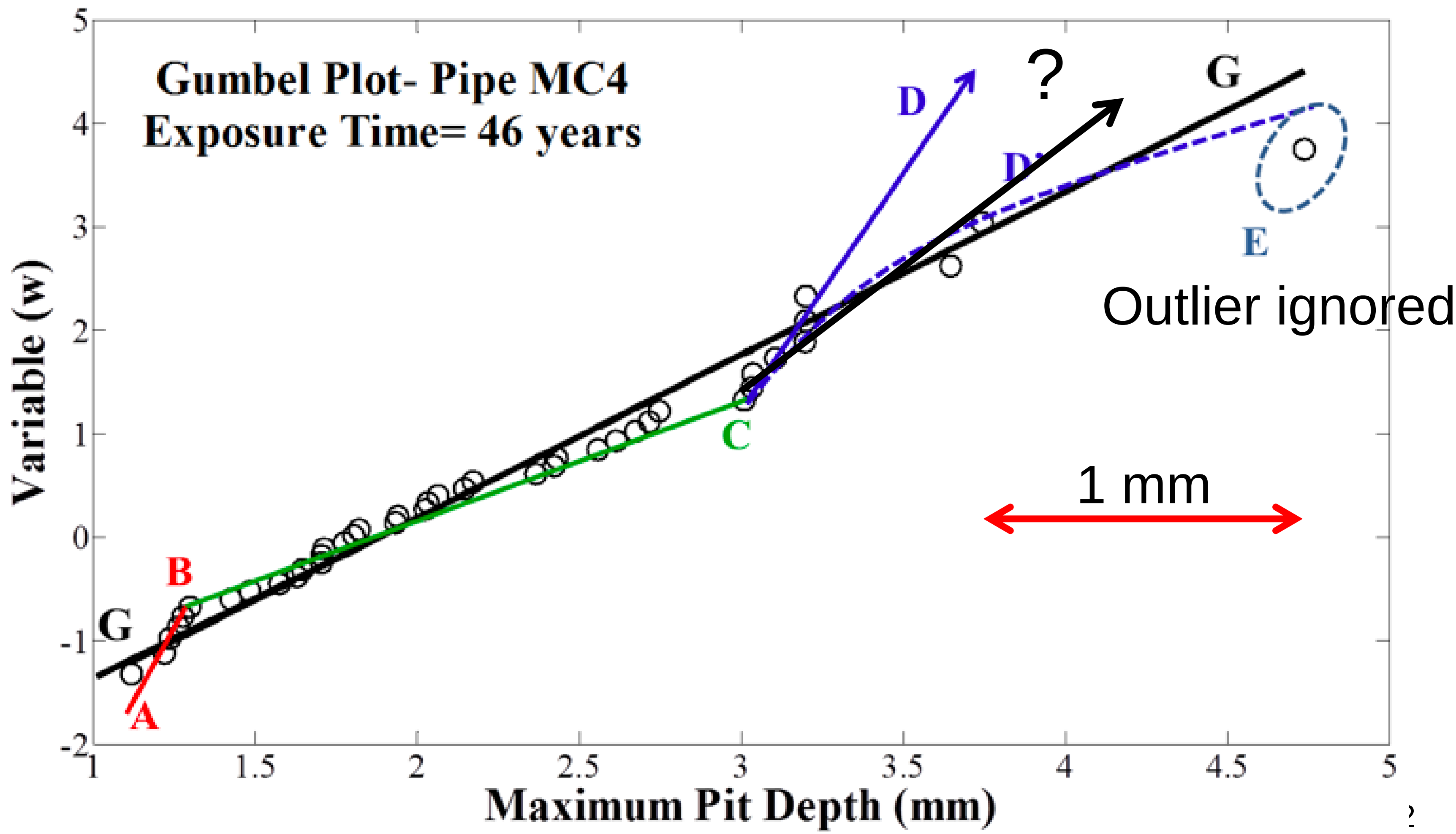
- Outlier extreme pit depth(s) removed (use Gumbel plot)
- Cohort of deepest pits retained



Outliers.
Possibly small material imperfections.



Typical example - data does not fit a Gumbel line!



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Modelling approach 4

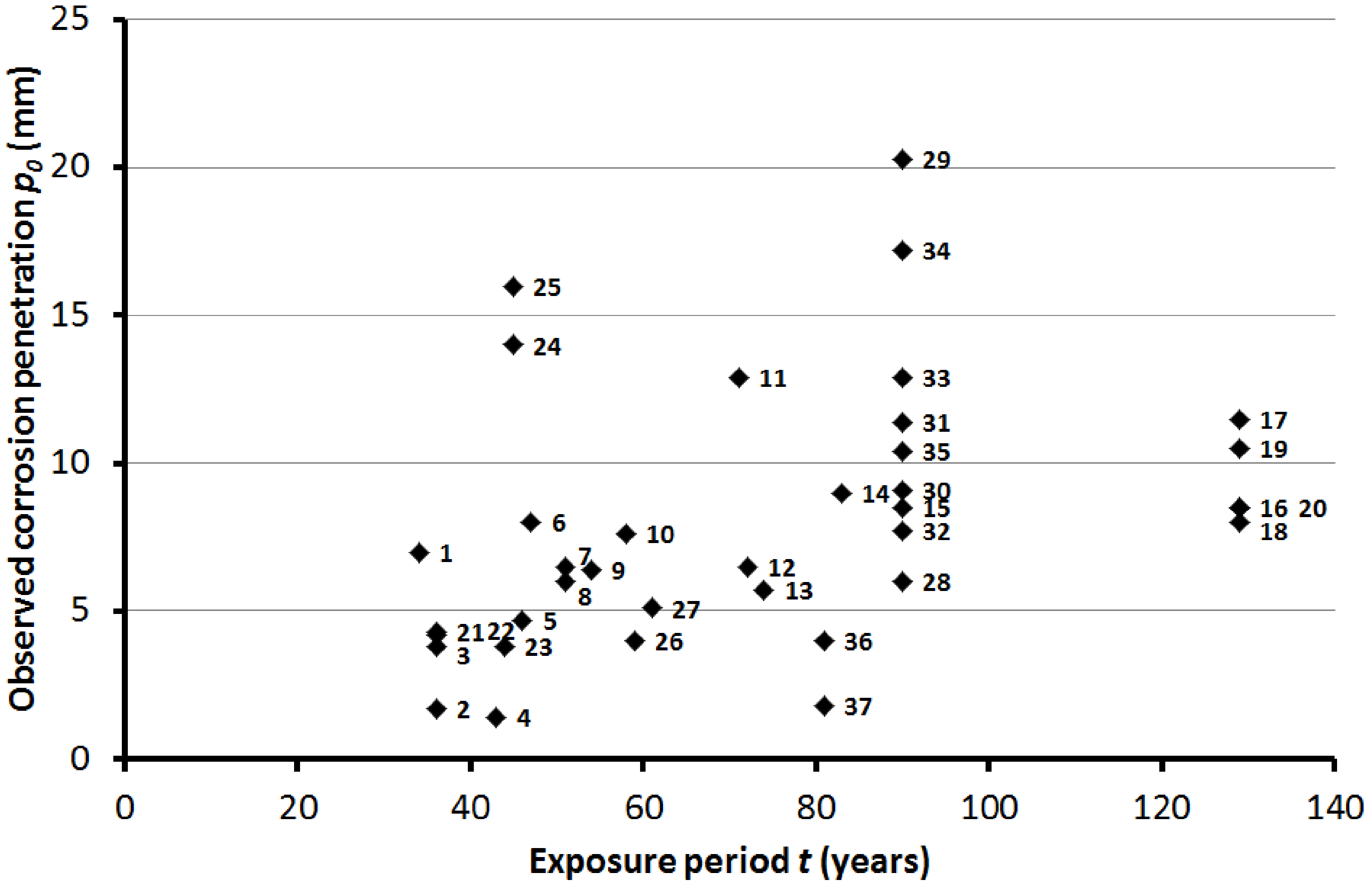

Figure 2. Observed corrosion penetrations p_0 versus exposure period t.

Modelling approach 5

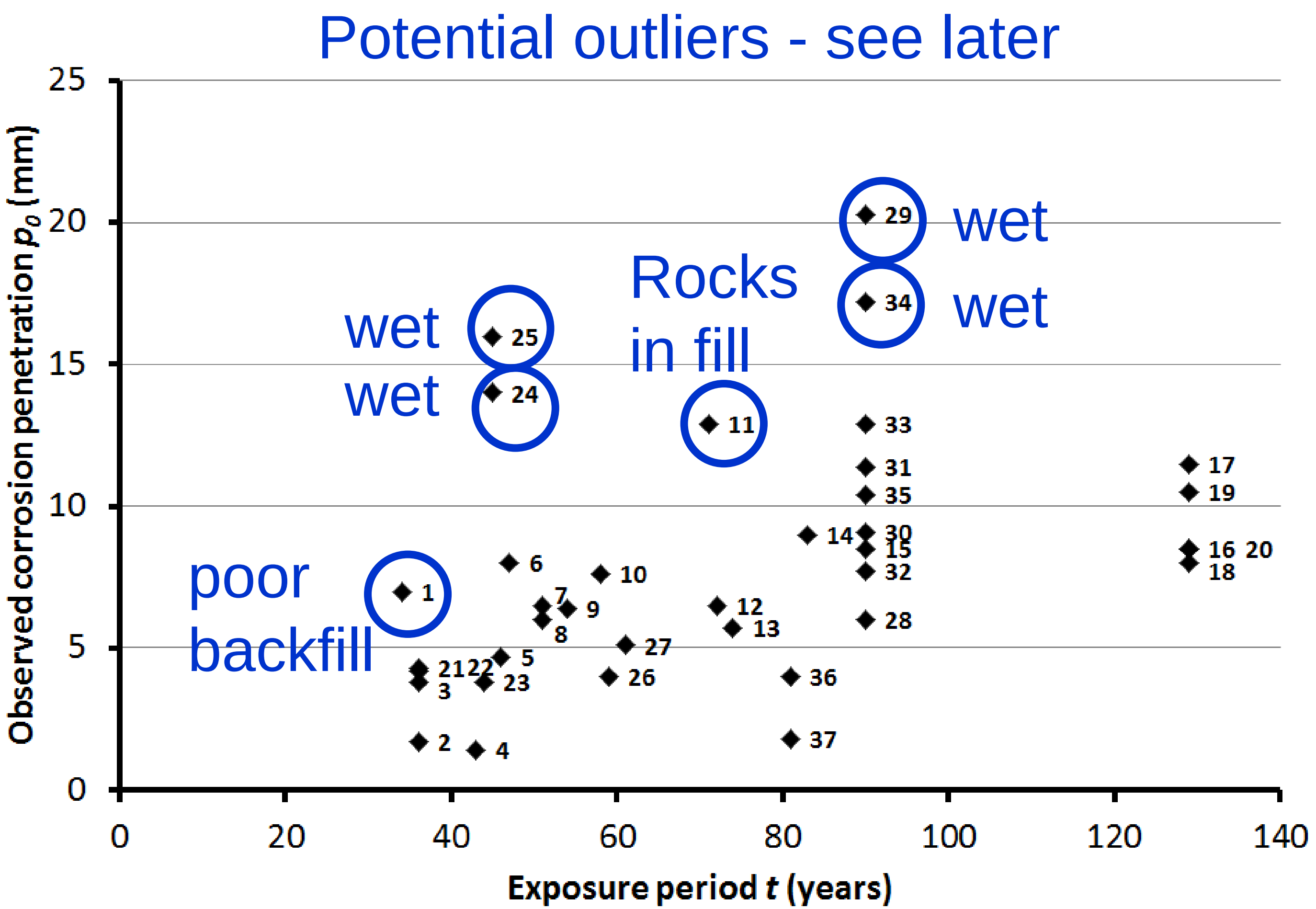

Figure 2. Observed corrosion penetrations p_0 versus exposure period t.

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Modelling approach 6

- Previous model (Mark I) was reviewed
- Previous model was based on standardising pit depth data to a standard moisture content (20% chosen)
- Can we improve soil moisture correction?
  - evidence suggests present approach is too simplistic?
  - refer to wetting of surfaces by soils vs. *mc*
- Further investigation of DIN and limits
- Refining other correction factors
- Mix of theory from other areas, insights, new data?
- Develop Mark II model

Adjust for time of wetness

- New approach is to model wetting of metal surface by soil
- Use ‘time of wetness’ concept from atmospheric corrn.
- Time of wetness = time that metal surface is wet enough to corrode significantly
- Field experience and previous analysis indicates high ‘time of wetness’ = significant corrosion

Adjust for time of wetness 2

- Gupta tests (1979) on sands and loams
- Low mc -> no corrosion
- Sharp rise as soil moisture reaches critical point (= 65% water holding capacity)
- (drop thereafter related to lack of O2. Ignore – long-term corrosion doesn't need much)
- Once mc reaches critical point enough water at surface for significant corrosion to occur.
- Time above that point = 'time of wetness'

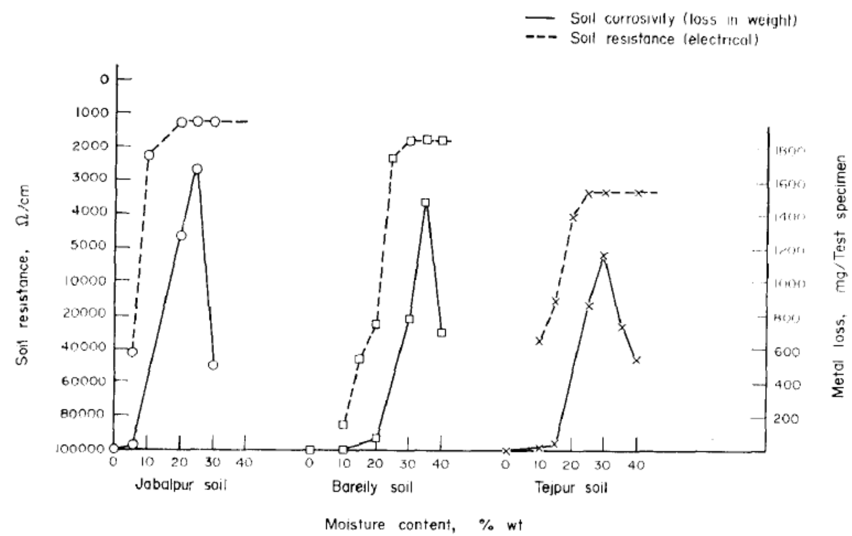

FIG. 1. Relation between soil corrosivity and soil resistance at different moisture contents.

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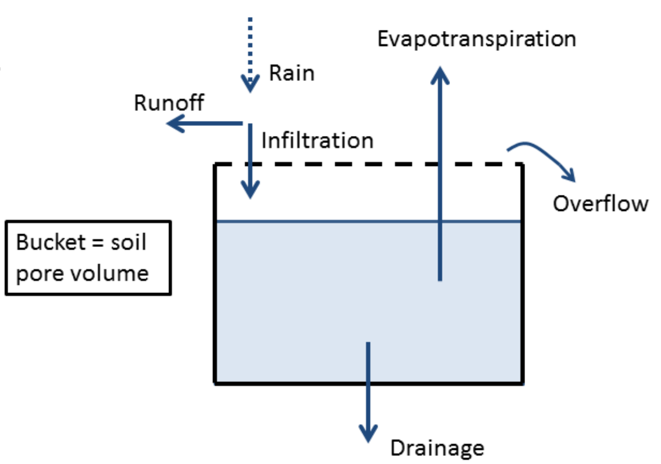
Adjust for time of wetness 3

- First estimate of a ‘time of wetness’
- Used simple climate soil moisture model
- To provide estimate of soil moisture variation with time
- First pass – calculated over a period of a year
- Number of days mc > critical point counted
- Used to calculate a % time of wetness
- <u>Adj. for ext. site factors (drains etc.)</u>
- Multiplied by exposure period to get ‘time of wetness’ over life of pipe



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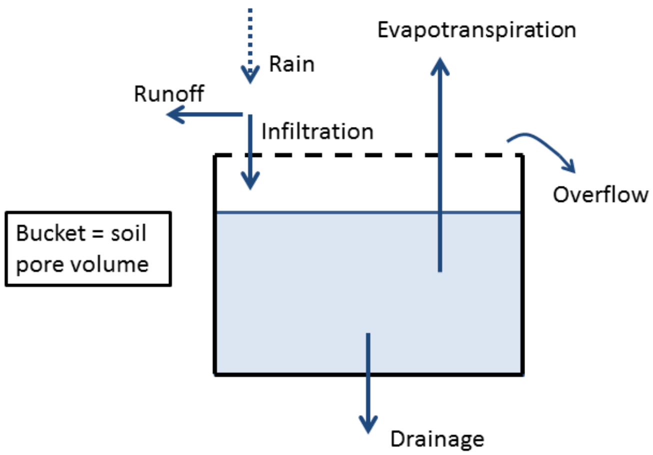
Adjust for time of wetness 4

- Notes on model:
- Inputs are -
- Daily rainfall and evapotranspiration
- Soil properties – moisture content at wilt point and field capacity, porosity (determined from bulk density tests), drainage factors (based on soil texture)
- Single bucket – only a single value of moisture across soil profile
- OK for first pass…



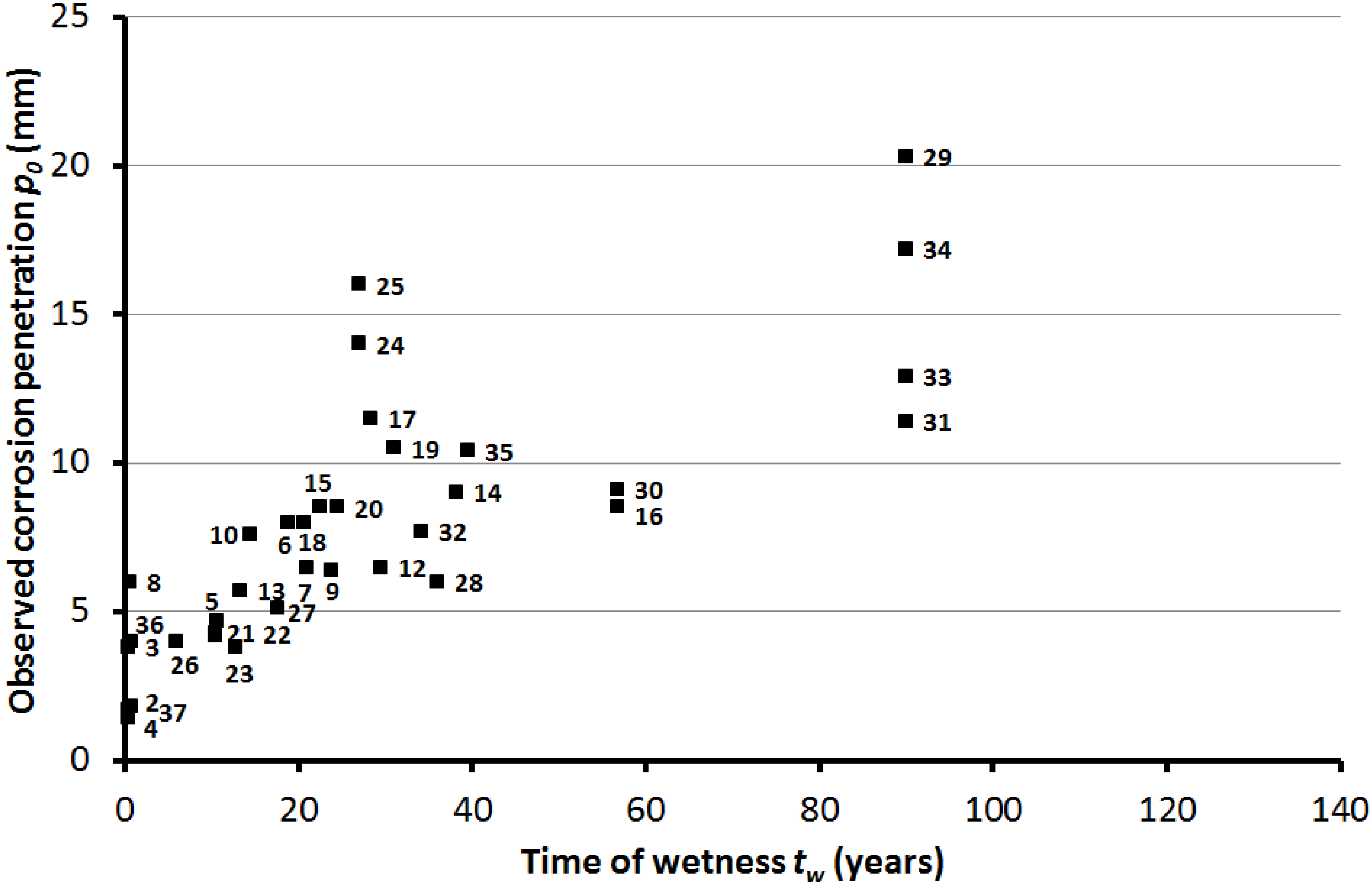


Figure 3. Corrosion penetrations p_0 versus time of wetness t_w. The scatter in the data is less than in Figure2. Also a much clearer trend has emerged.

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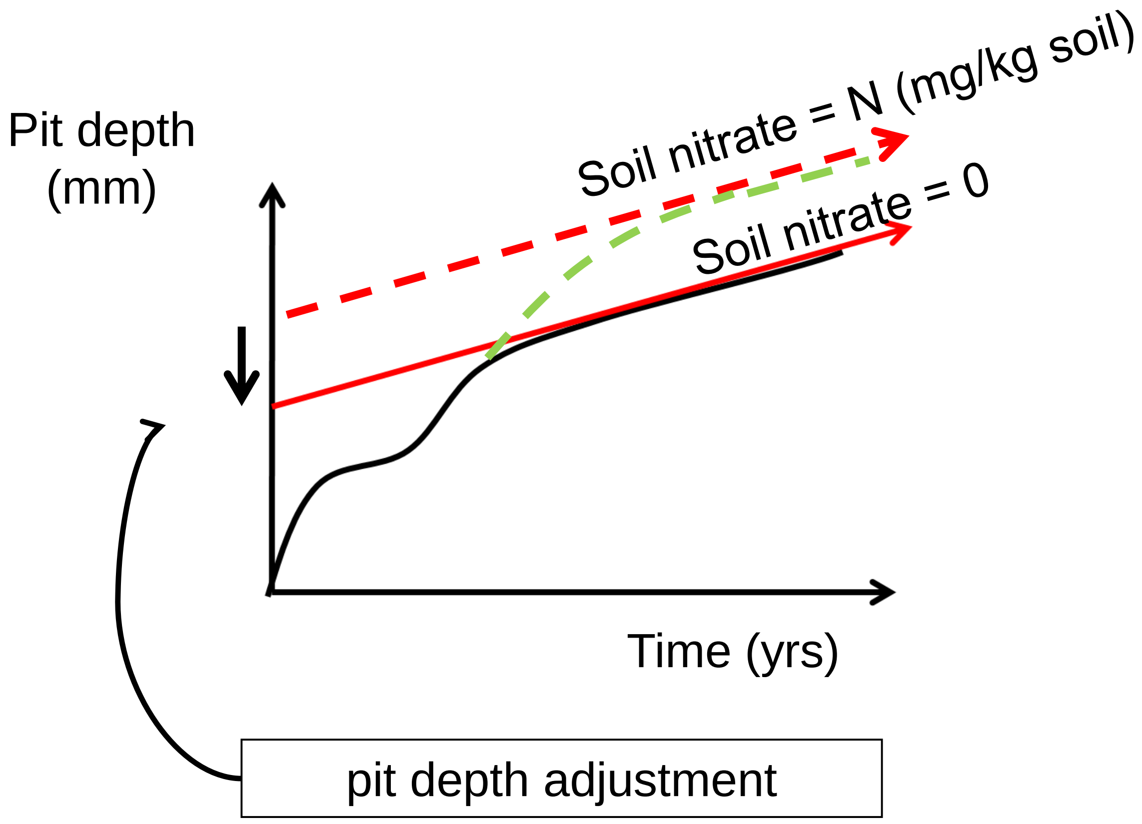
Nitrate (nutrient) adjustment 1

- Estimate for N adjustment



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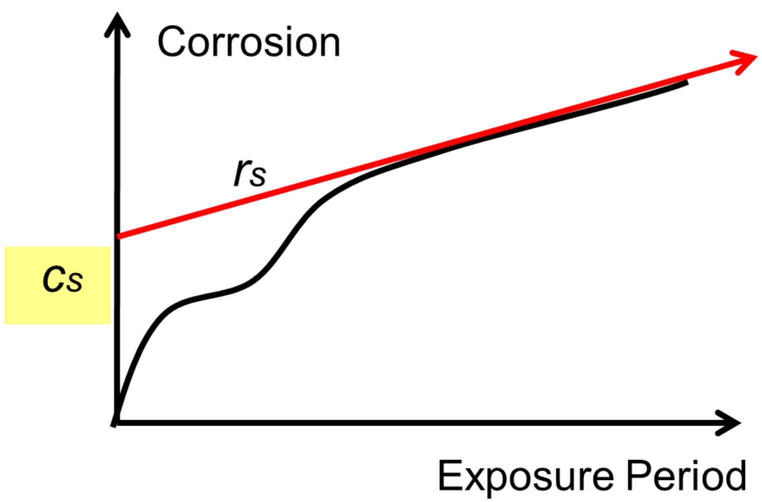
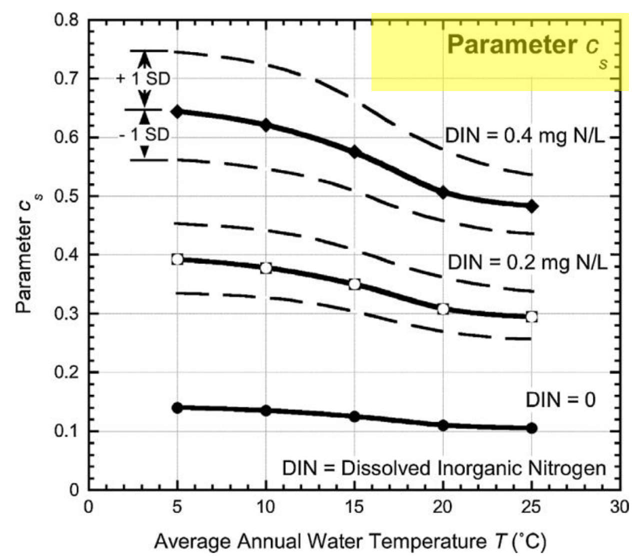
Nitrate (nutrient) adjustment 2

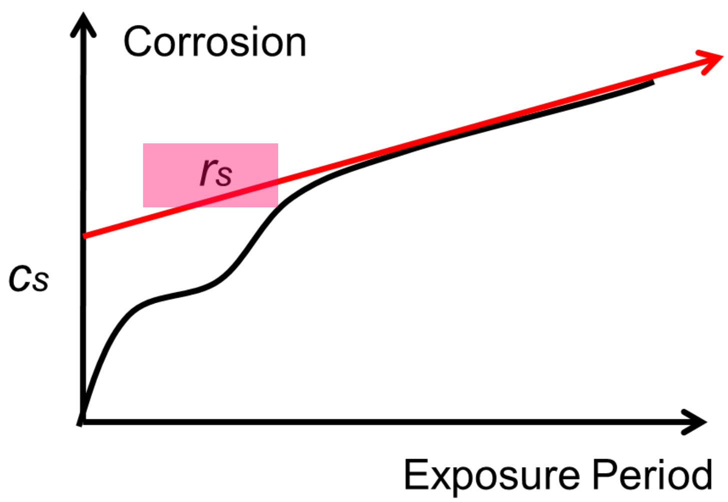
- Based on findings from recent work (Melchers 2014)
- Influence of dissolved inorganic nitrogen (DIN) on the corrosion loss of structural steel immersed in seawater

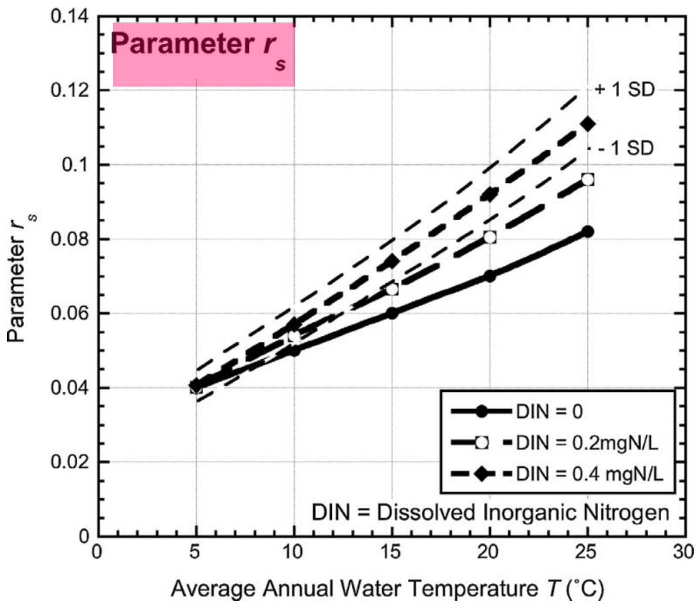




Nitrate (nutrient) adjustment 3

- Based on findings from recent work (Melchers 2014)
- Influence of dissolved inorganic nitrogen (DIN) on the corrosion loss of structural steel immersed in seawater





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Nitrate (nutrient) adjustment 4

- Main assumptions in determining N adjustment:

1. Main component of DIN = Nitrates (N) in long term
2. Nitrate (N) is the limiting nutrient in a soil
3. Long-term corrosion mechanisms at the corrosion surface (under rusts) are the same for immersion and soil environments
4. Thus expect similar influence of N on long-term corrosion
5. Main effect of N is on parameter c_s (r_s ignored)

Adjust for DIN (nitrates) = nutrient for MIC

A first estimate for the relationship between the increase in depth Δp_{MIC} of the deepest penetration cohort as a result of MIC fostered by soil nitrates N (mg N/kg) is:

$$\Delta p_{MIC} = c_{sN} = 0.5N$$

The greatest influence of MIC is during Phase 3 of the corrosion process. It was assumed that the above adjustment only applied to sites where t_w was beyond this point. [determined as 20 years]

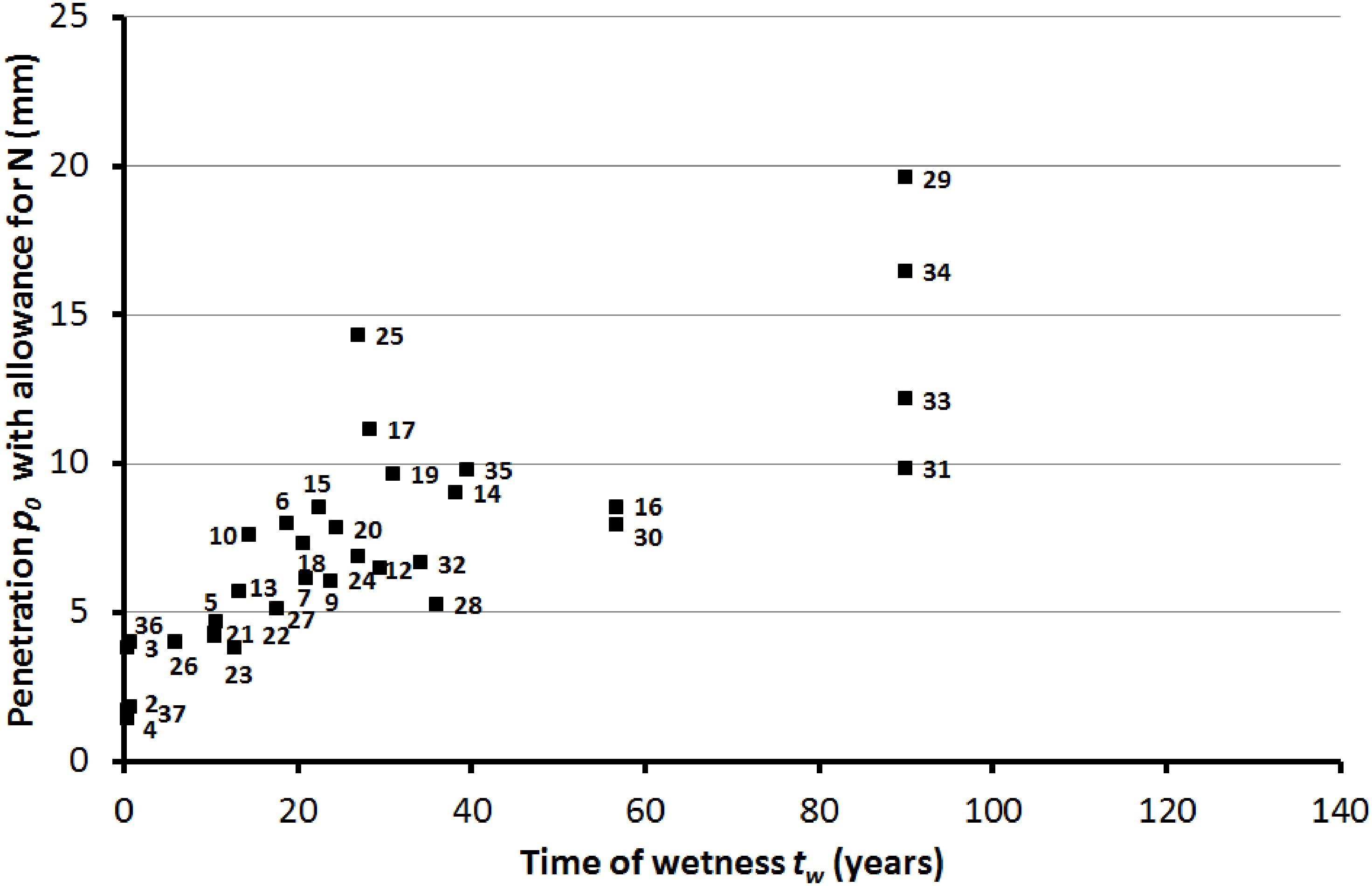

Figure 4.Corrosion penetrations p_0 with allowances for soil nitrate content, versus time of wetness t_w. The scatter is somewhat less than in Figure 3.

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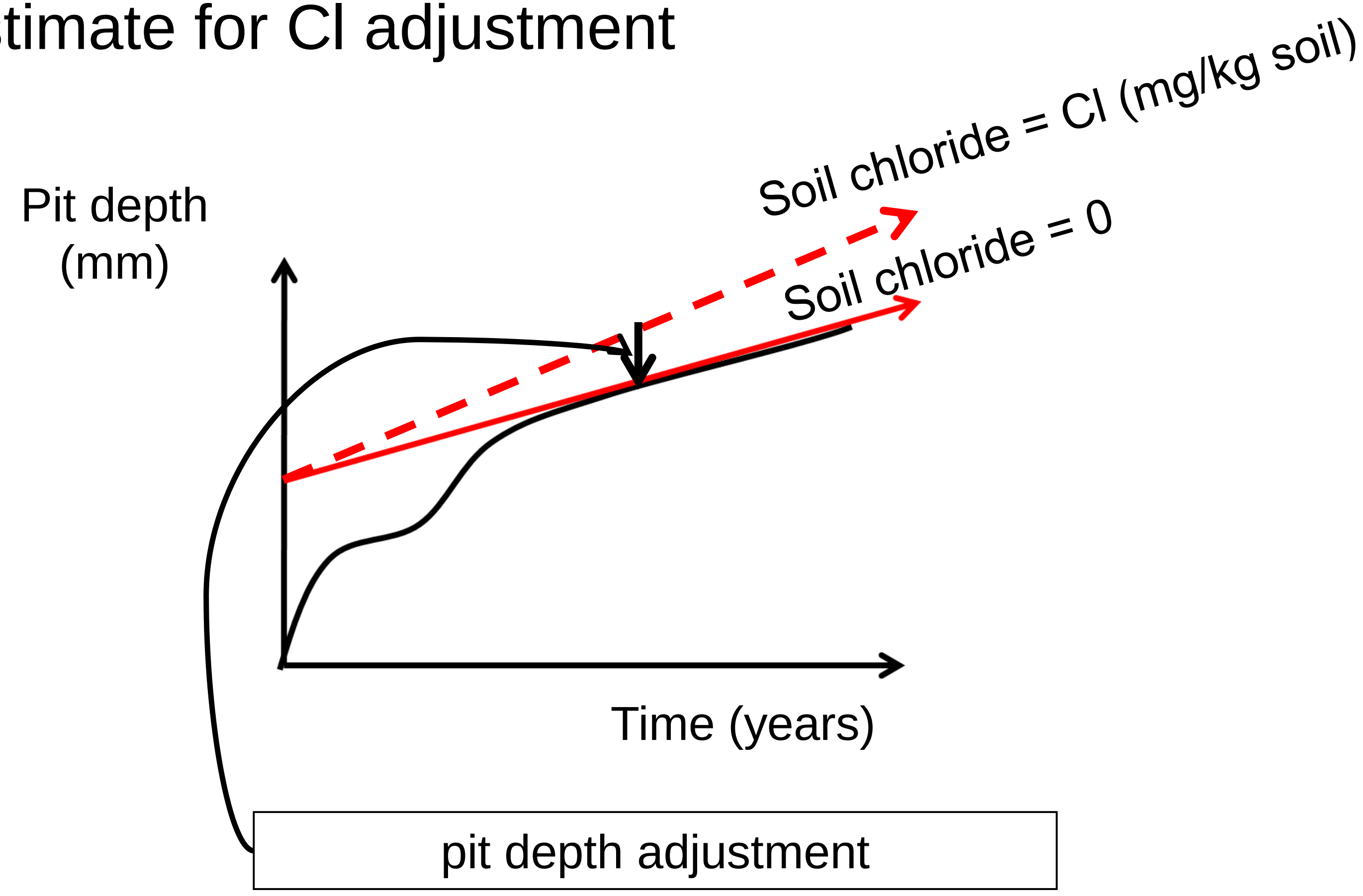
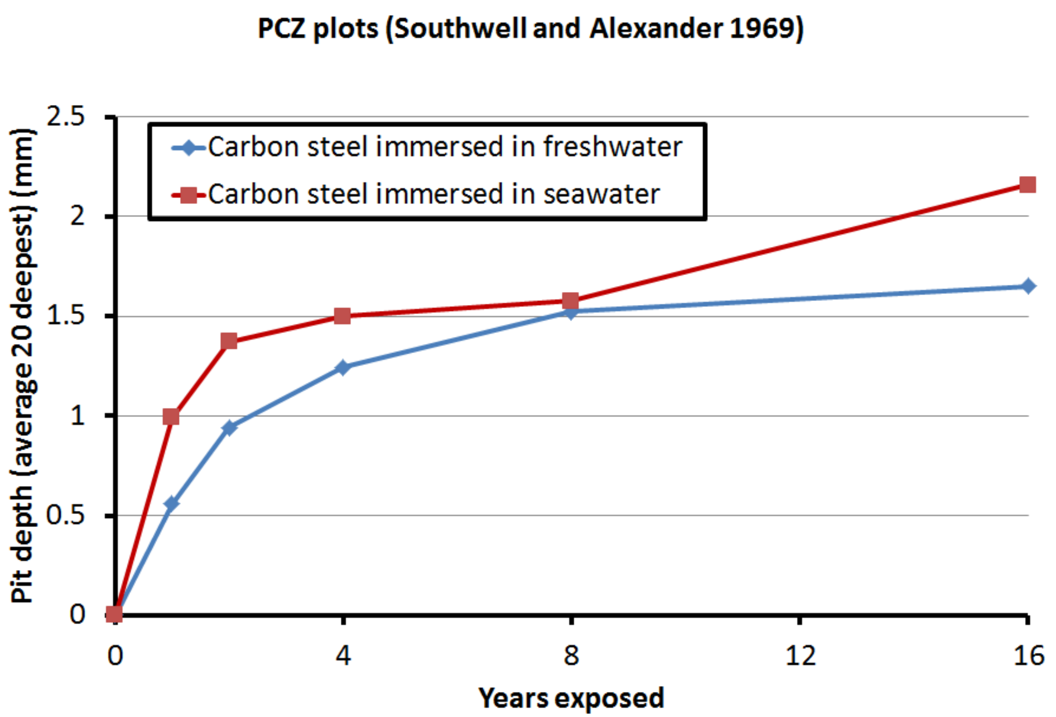
Chloride adjustment (1)

- Estimate for Cl adjustment



Chloride adjustment (2)

- Based on long-term corrosion rates of carbon steel in fresh and seawater immersion from Panama Canal Zone
- Assumed similar effect for long-term corrosion of cast iron in soils



Adjust for chlorides

Based on comparison between freshwater and seawater corrosion, scaled:

Correction Δp_{cl} at any time t_w to corrosion penetration for soil chloride concentration is given by:

$$\Delta p_{Cl} = r_{sCl}.t_w = 8 \times 10^{-6}\, c_{Cl}.t_w$$

Where t_w is the relevant time of wetness and c_{Cl} is the local chloride concentration (in mg Cl/kg) in the soil.

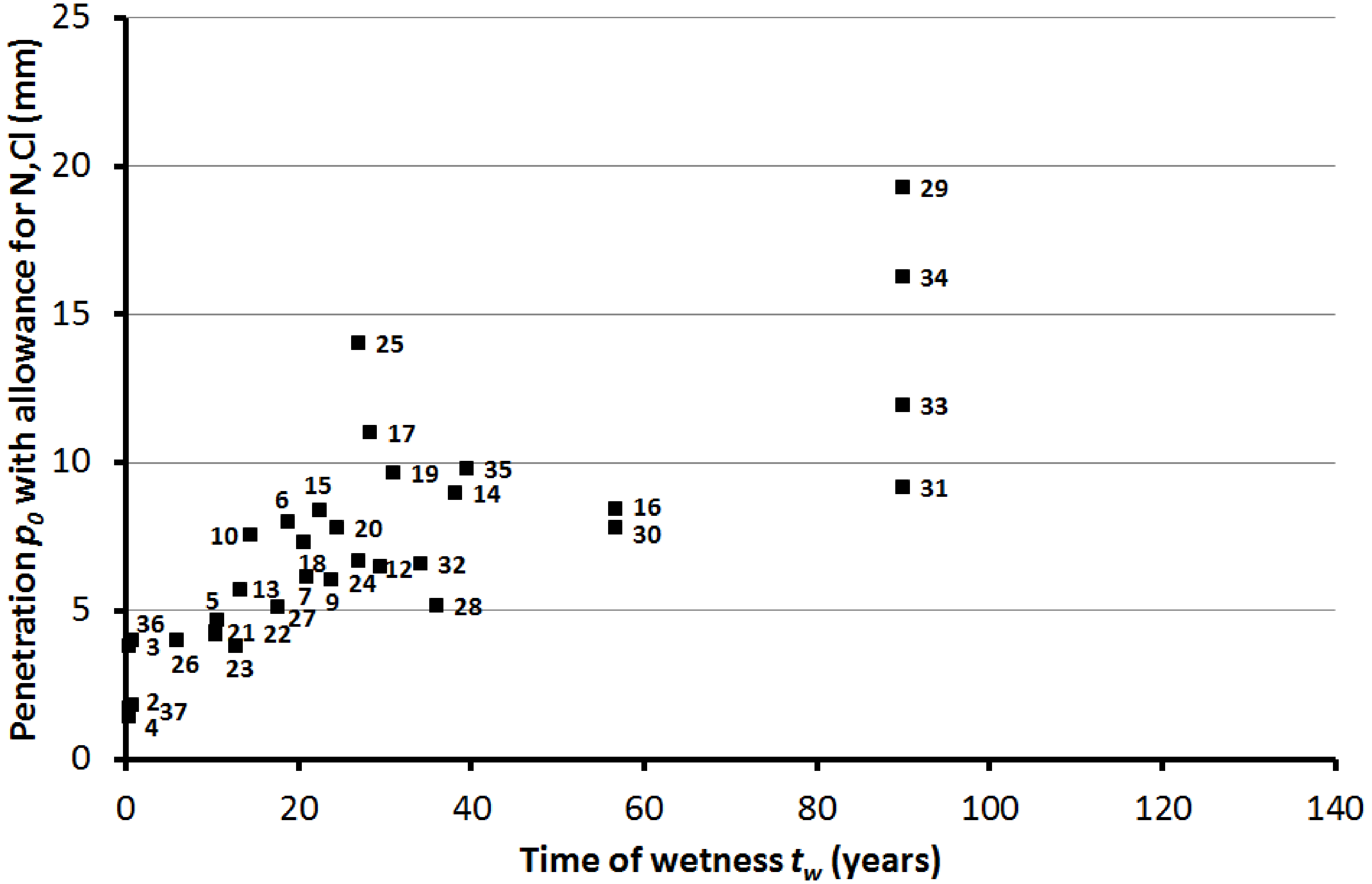


Figure 5.Corrosion penetrations p_0 with allowances for soil nitrate and chloride content, versus time of wetness t_w. The scatter in the data is almost the same as in Figure 4.

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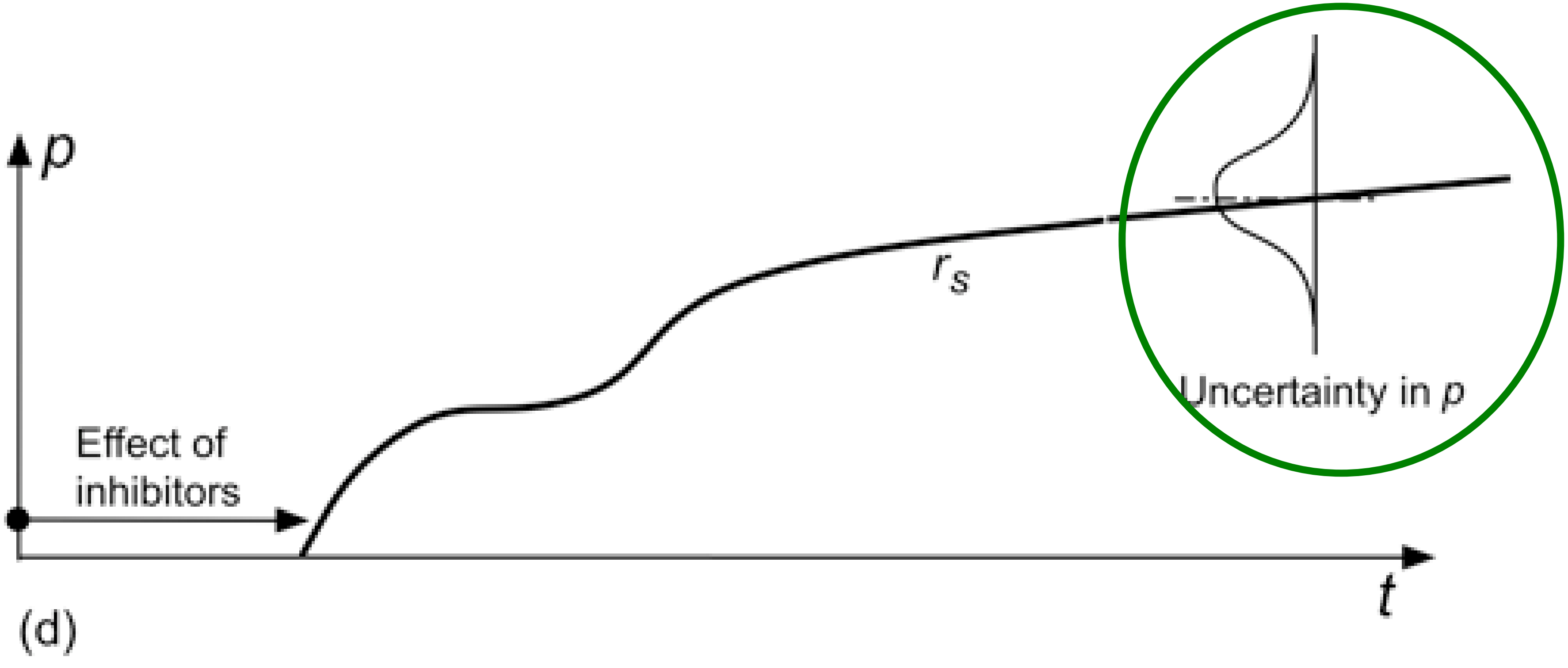
Phosphate/Carbonates adjustment

- These are corrosion inhibitors – delay initiation of corrosion
- Shifts function to the right
- Little effect on *p* for long-term -> Ignore their effect



Mean Trend and Uncertainty - add percentiles (from SDs)

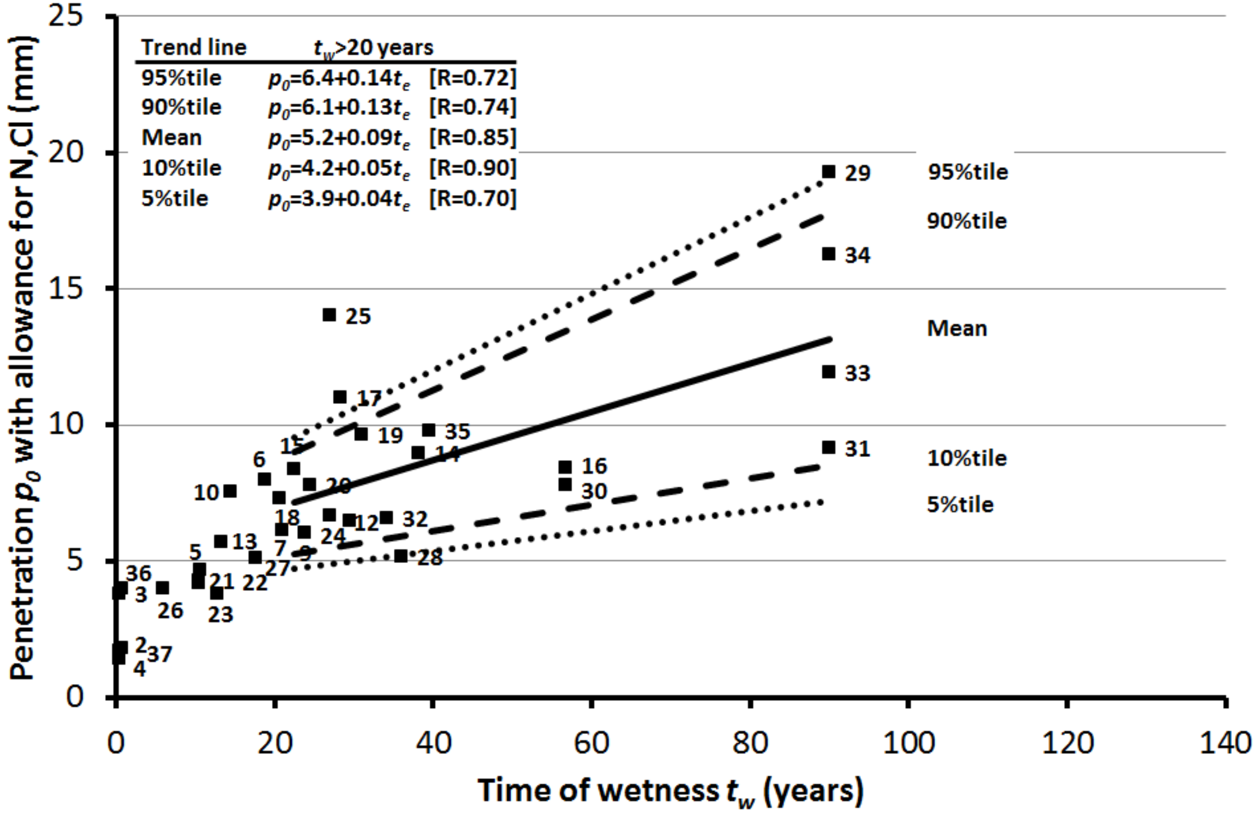


Figure 6.Corrosion penetrations p_0 *with allowances for soil nitrate content and soil chloride content versus time of wetness* t_w*. Mean value and percentile trend lines are shown for* t_w*>20 years.*

To predict corrosion - for cast iron in soils

Estimate time of wetness t_w

Use trend line
=> p_0 at time t_w

$$p(t_w) = p_0(t_w) + \Delta p_{MIC} + \Delta p_{Cl}$$

correct for DIN

$$\Delta p_{MIC} = c_{sN} = 0.5N$$

correct for chlorides

$$\Delta p_{Cl} = r_{sCl}.t_w = 8 \times 10^{-6}\, c_{Cl}.t_w$$

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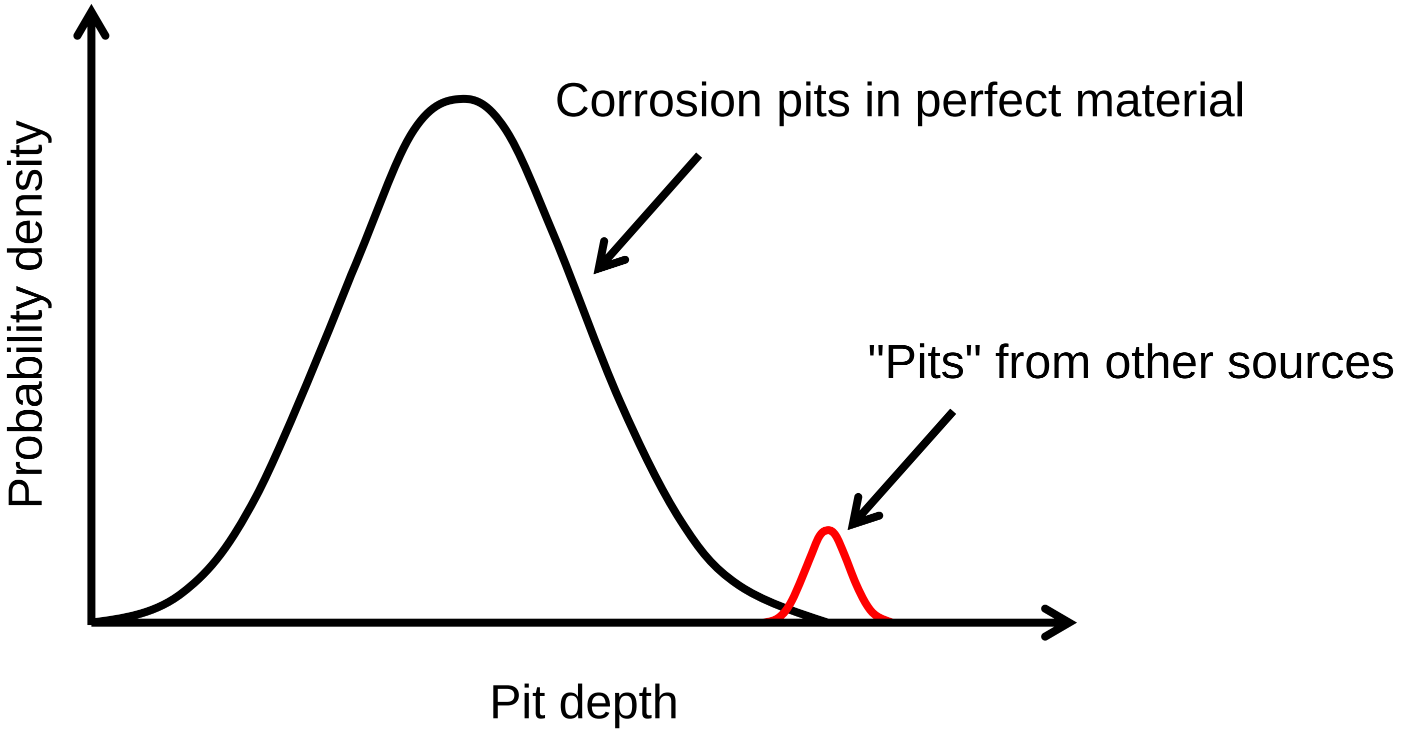
Other effects - outliers

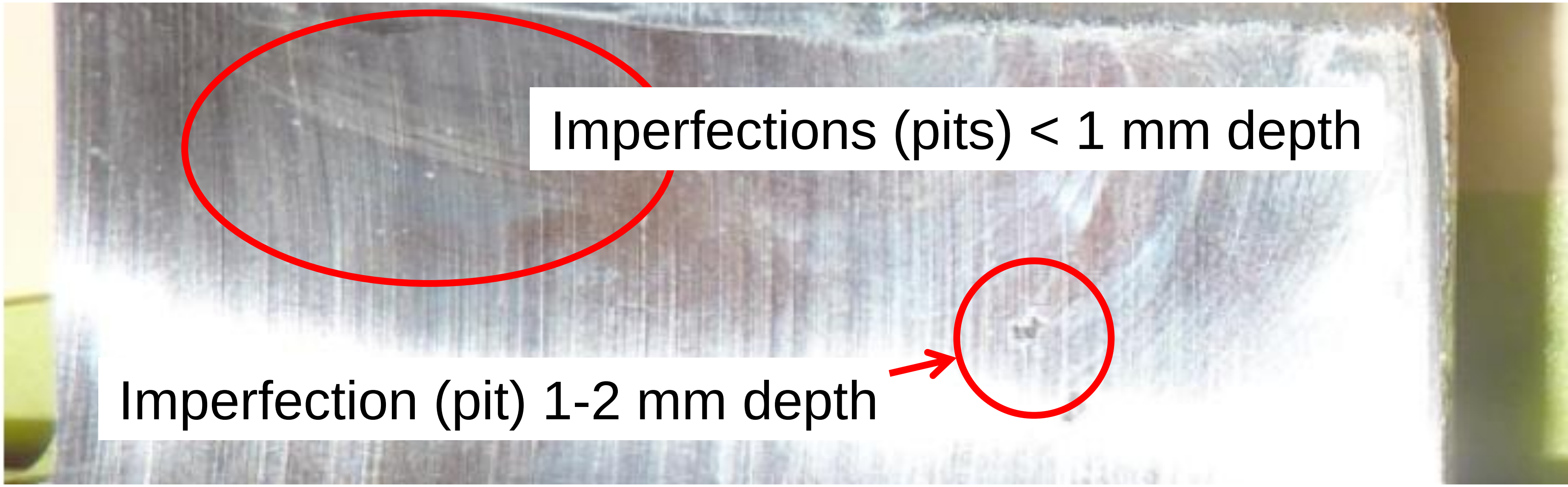
- Separate probability functions for corrosion pits in perfect material and apparent pits from other sources



Imperfections in cast iron:

Observations show these will always be present - and they will be measured as ‘pits’ even though they are not, and have no mechanism for growing in depth.

They may be much larger than pits - hence the high extremes sometimes seen. If small they get lost in the pit depths….

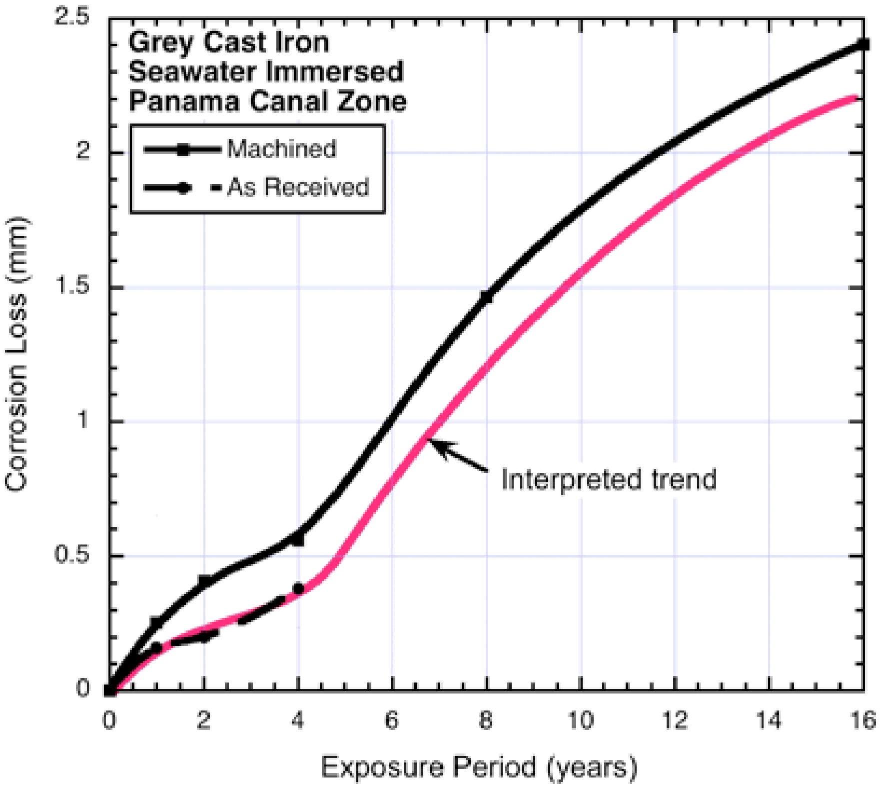


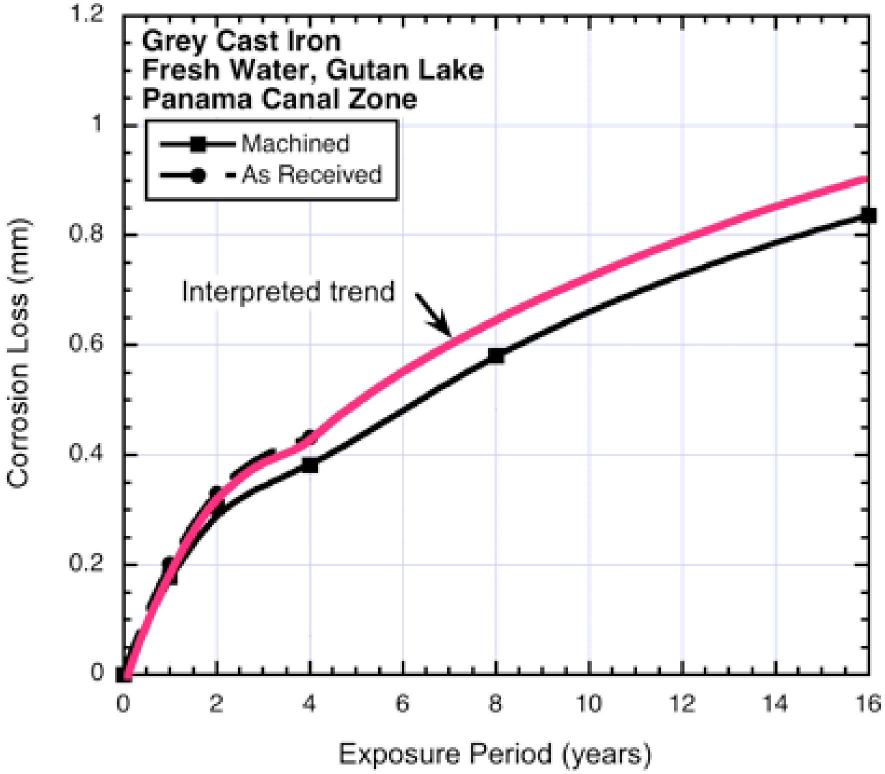
Rock and hard rubbish damage

Could damage casting layer - increase corrosion

Requires further investigation + modelling.

Risk factor for water utilities ...





Clay lumps stuck hard to pipe: Causes localized corrosion under the lumps. Depth of this will be about the same as depth generated by one cycle of pitting.

Also see pipe with rope prints.

Requires further research + modelling.

Figure 8. Localized corrosion on the exterior of a cast iron pipe showing the clearly defined pattern of ropes presumably used to install the pipe but not removed prior to burial. The rope has since rotted-away but the imprint from localized corrosion remains. The white dots are orientation marks for laser scanning of the pipe surface.

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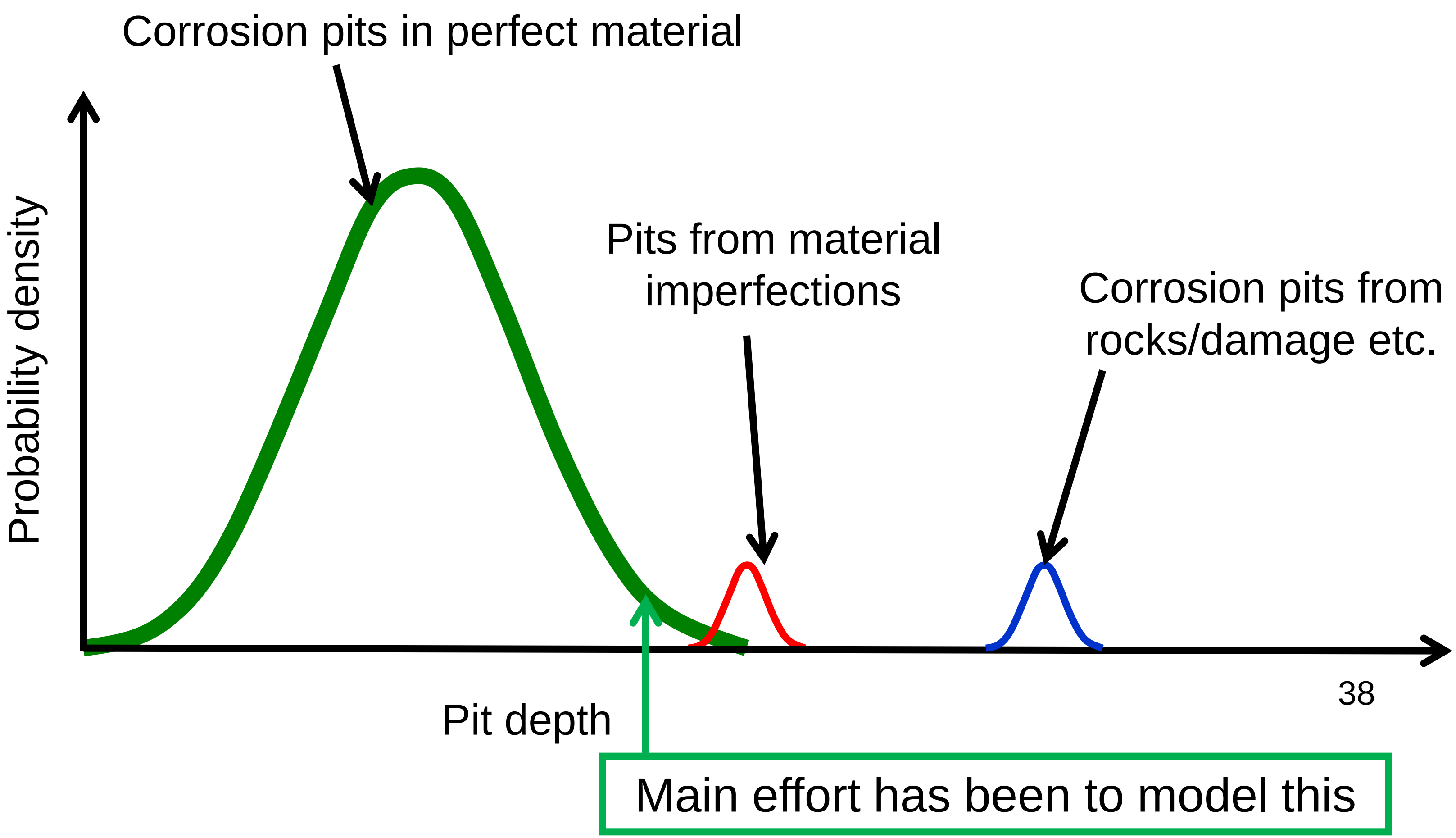
Discussion – prime objective pit depth vs. soil



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Discussion – historical data

- Previously others (and us) tried using historical data (Romanoff 1957) to calibrate a model
- Unsuccessful because available data does not fit main requirements for corrosion:
  - No N, P data. Limited moisture data.
  - No pit statistical data
  - Cannot isolate corrosion from imperfections
- Make more sense out of data considering ‘time of wetness’?
- Data protocol adopted by HW, SW + others is now providing

  - 3D scan information for localized corrosion, statistics

  - relevant soil parameters – *mc*, nutrients, those to estimate t_w....

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Discussion – corrections for N, Cl, etc.

- Proposed corrections reduce scatter in pit depths
- Trends for corrected pit depths as a function of time of wetness are reasonable
- Influence of N, Cl on pit depths in soil now clear
- Effects of P, carbonates also, but require more work
- Method used to estimate time of wetness was found to be adequate, but still there is room for improvement

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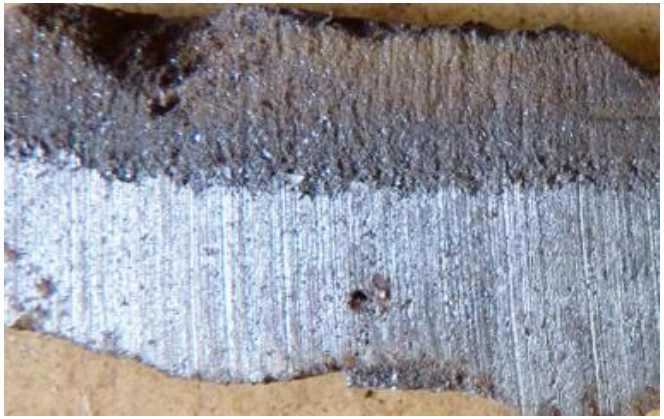
Discussion - outliers

- Not discussed in any standard text, papers
- Field staff have been main informants
- Also our own observations for other CI projects
- Adds substantial IP to the project
- Likely to have practical implications
- Suggests more research is required



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Discussion – Corrosion measurements for CI pipes

- What are the requirements for measurement of corrosion for in-situ pipes?
- Relating to pipe failure (Activity 1)…
- The average thickness loss is not of much interest
- The deepest pits are important – but only if their depth is approaching pipe wall thickness
- Any patch corrosion is particularly important

Discussion – Patch corrosion surrounding perforation

- Our take-
- Pitting perforates pipe, which allows leakage of O2 rich water from inside pipe, through the CL, to under the rusts and graphitized layer
- New rapid continuous corrosion under O2 conditions occurs on the outside of wall but under graphitised layer -> large area of general corrosion

- Indicates need to add another stage to overall modelling

Future work

- Current work has shown the important influence of '**time of wetness**' for soil corrosion
- Method used to estimate time of wetness was found to be adequate, but still room for much improvement
- Method based on wetting of surfaces by sands and loams (not clays) – proposed lab tests to investigate clays (funded)
- Water utilities might take note of local conditions that could elevate of otherwise influence time of wetness at the pipe-soil interface
- This knowledge required for est. of t_w

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Future work

- Better **corrosion penetration** measurements (scans before and after grit blasting – out of round issue)
- Up-date protocol to reflect these ...
- ***Education required of why protocol is so important.***

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Future work

- Research on ‘outliers’ and how to model their effect, and how to describe them

- Development of probabilistic corrosion prediction tools
  - to assist risk assessment
  - to include outlier type effects and prob. of occurrence
  (on-going) ('extra' for project)

- Development of model for pit size vs. depth (on-going) – UoN PhD project – agreed part of new work.

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Future work

- Extend corrosion model to cast iron *reticulation* pipes
- These are no different to CI mains (just size)
- Would extend overall impact of project outcomes

- Preliminary discussions with Hunter Water - likely to 'come on board' with data

- Other water utilities?

Thanks