TEXAS A&M UNIVERSITY

Homero Castaneda, FNACE
Professor
Director of the National Corrosion and Materials Reliability Laboratory

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Soluciones Sostenibles en el Mantenimiento y Rehabilitación de Infraestructuras Corroídas

Background

- Production of Metals stands for
- 40% of all industrial greenhouse gas emissions
- 10% of the global energy consumption,
- 3.2 billion tones of minerals mined (2 billion of metals produced daily) and several billion tones of by-products yearly.

[Raabe et al, Chem Rev. 123 (2023) 2436-2608]

A circular economy model does not work (yet) because market demand exceeds the available scrap currently by about two-thirds.

What can we do?

CO_2 reduction by CO_2-free production and by increasing the lifetime of products.   Time-dependent treat Corrosion Science and Engineering

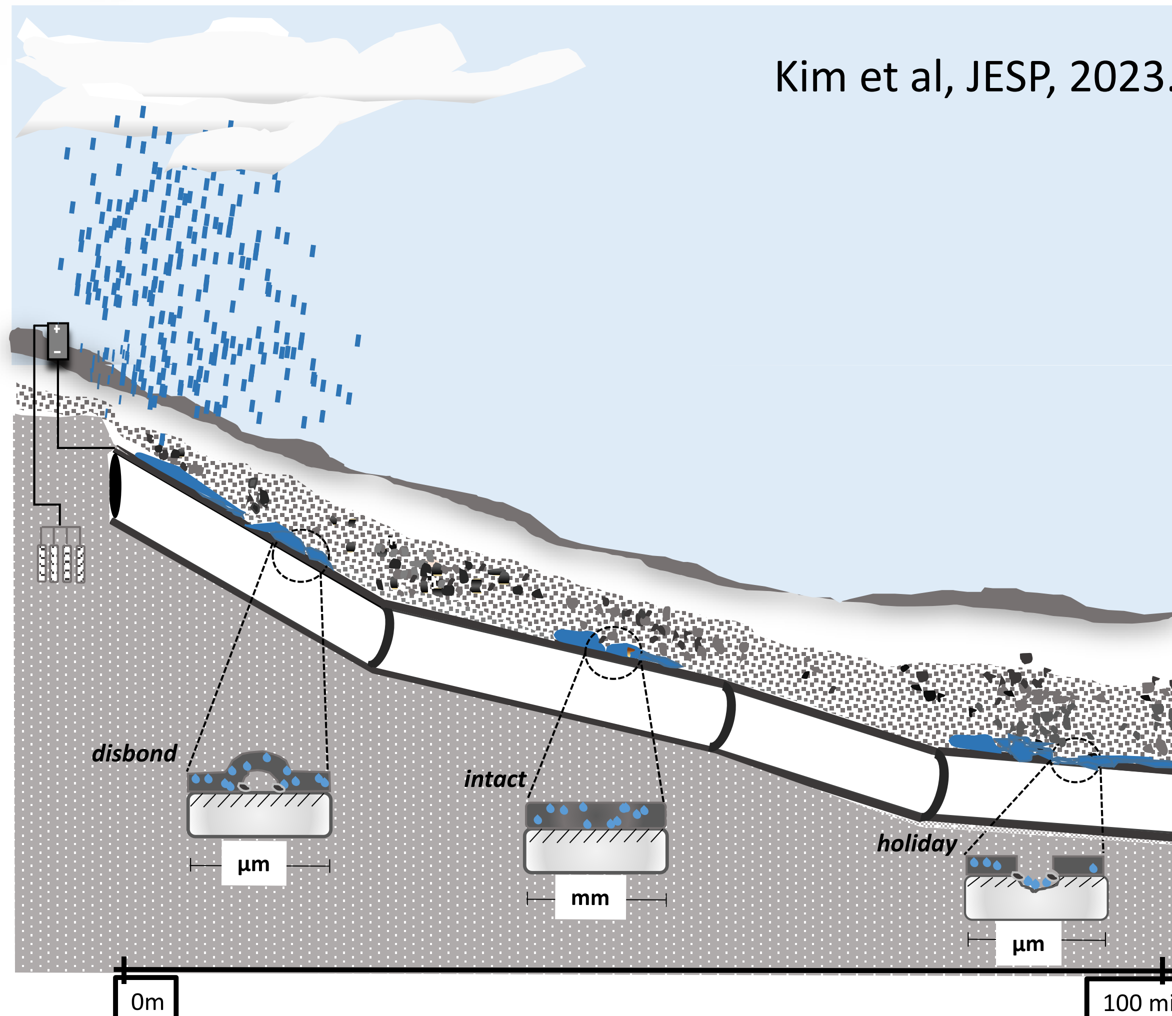
Data drive modeling –When to repair/Inspection/monitoring

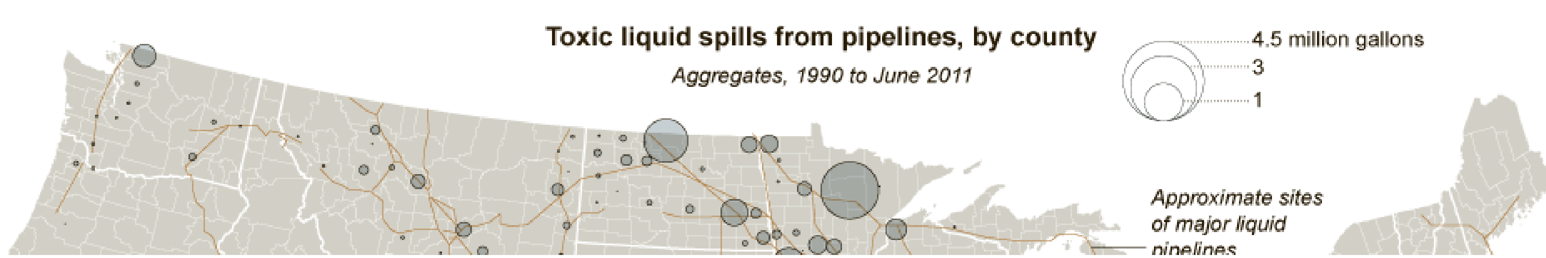
- It is not how it is where and when.

When I can repair it?

Where I can repair it?

We will cover the concepts, technology, and solution in one strategic application:





Current corrosion assessment methods (analysis)…

- cannot quantify to prioritize digging sites.
- are subjective depending on experiences.
- do not consider uncertainties comprehensively.

COUNTY, TEX. Third-highest volume, with 2.9 million gallons.

HARRIS COUNTY, TEX. Houston's county, had the highest volume, with 4.5 million gallons in over 200 spills.

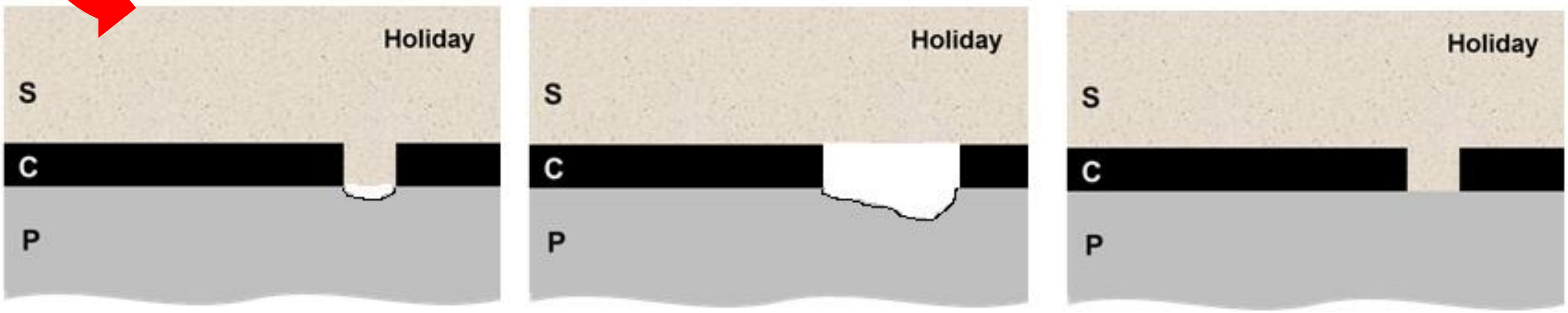
and distribution nexus. Jefferson Davis Parish had the second-highest volume, with 3.2 million gallons. Plaquemines Parish was the fourth, with 2.8 million gallons.

Source: Department of Transportation, Pipeline and Hazardous Materials Safety Administration (http://phmsa.dot.gov/)

❑ A sustainable repair/maintenance should be approached with fundamentals

For example, ECDA is a four-step process for assessing the integrity of a section of a pipeline:

- **Pre-assessment (Electrochemical Fundamentals and Modeling)**
- **Indirect inspections (Defined electrochemical system- Modeling for technologies)**
- **Direct examination- based on modeling**
- **Post-assessment- based on modeling**



ECDA (NACE SP0502)- modifications

1) *PRE-ASSESSMENT*

External Corrosion Threat → **Data Collection** → Indirect Inspection Tool Selection → Define ECDA Regions

2) *INDIRECT INSPECTION*

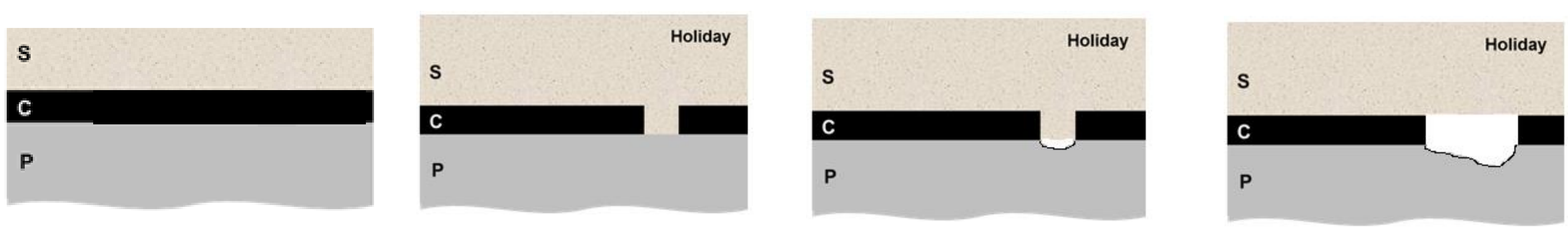
Conduct Indirect Inspection → Inspection Data Alignment → Severity Classification

3) *DIRECT INSPECTION*

Set Dig Priority → Dig and Data Collection → Remaining Strength Evaluation

4) *POST ASSESSMENT*

Root Cause Analysis → Remaining Life Calculation → Define Interval of Reassessment → Define Effectiveness Measure



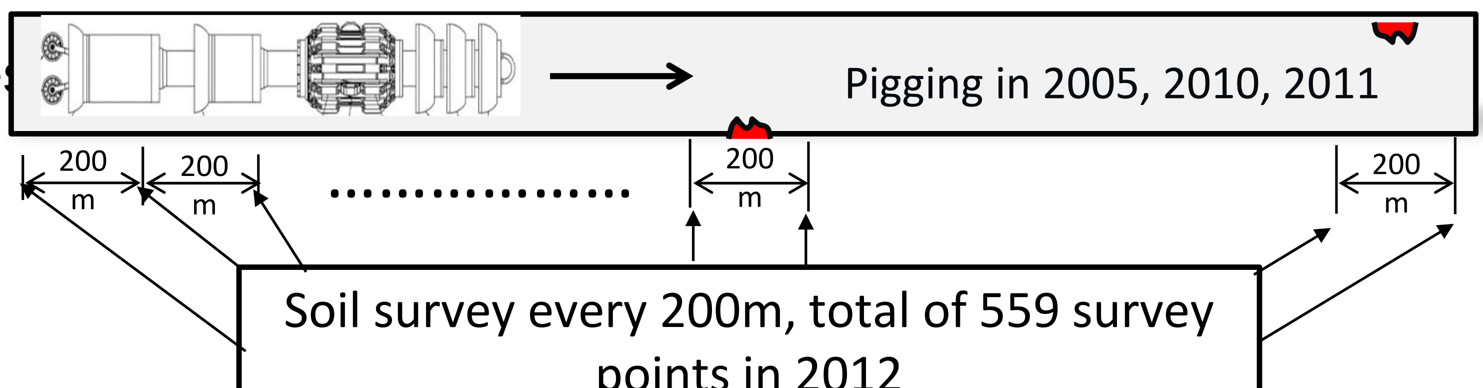
Case of Study -ECDA

Gas pipeline

Length	110 km
Diameter	457.2 mm
Wall thickness	6.41 mm
Steel type	API 5L X52
Minimal yielding stress	52 ksi
Coating	Coal tar
CP	Impressed current

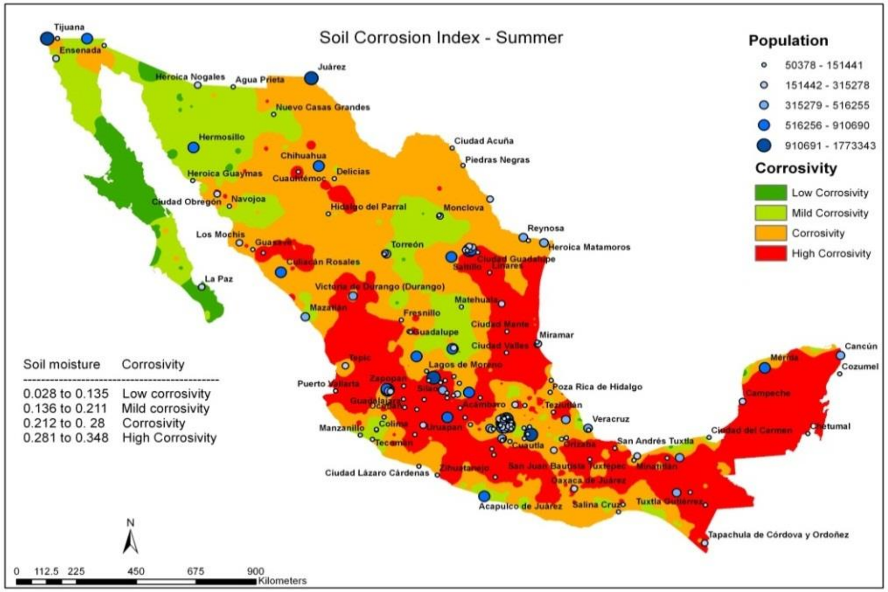
Elevation	
Min	98m
Ave	876m
Max	2548m
Slope	
Max	35%, -35.2%
Min	5.2%, -5.7%

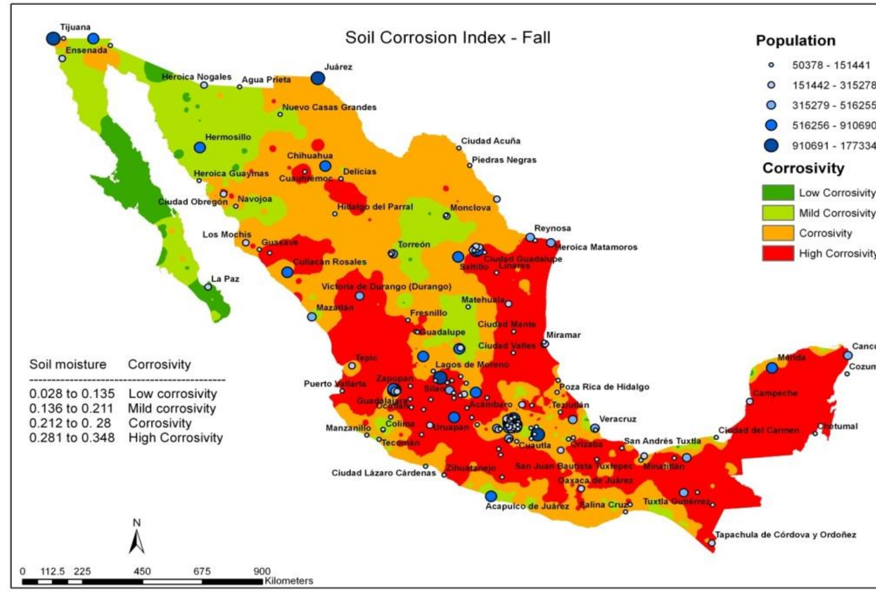
~68miles

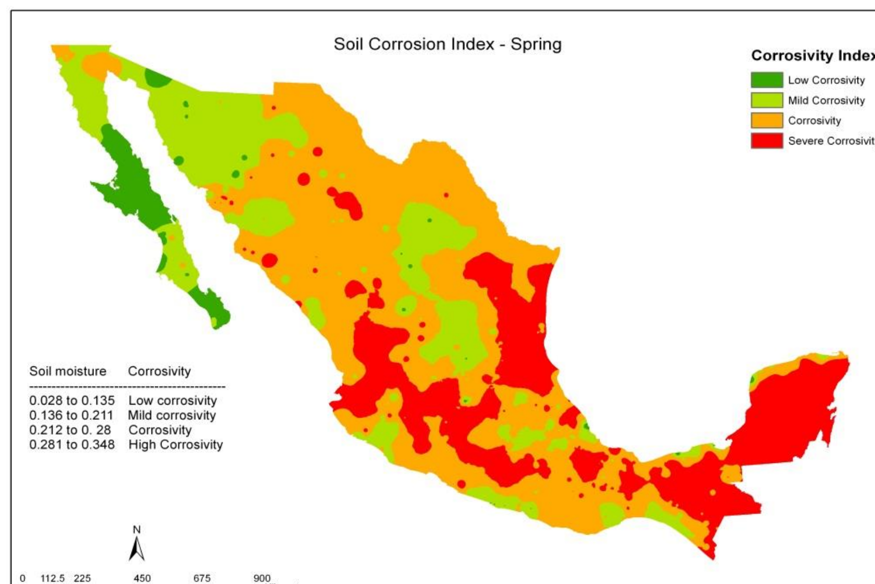


Corrosivity Map based on Macro-parameters

pH, soil resistivity, ionic sampling

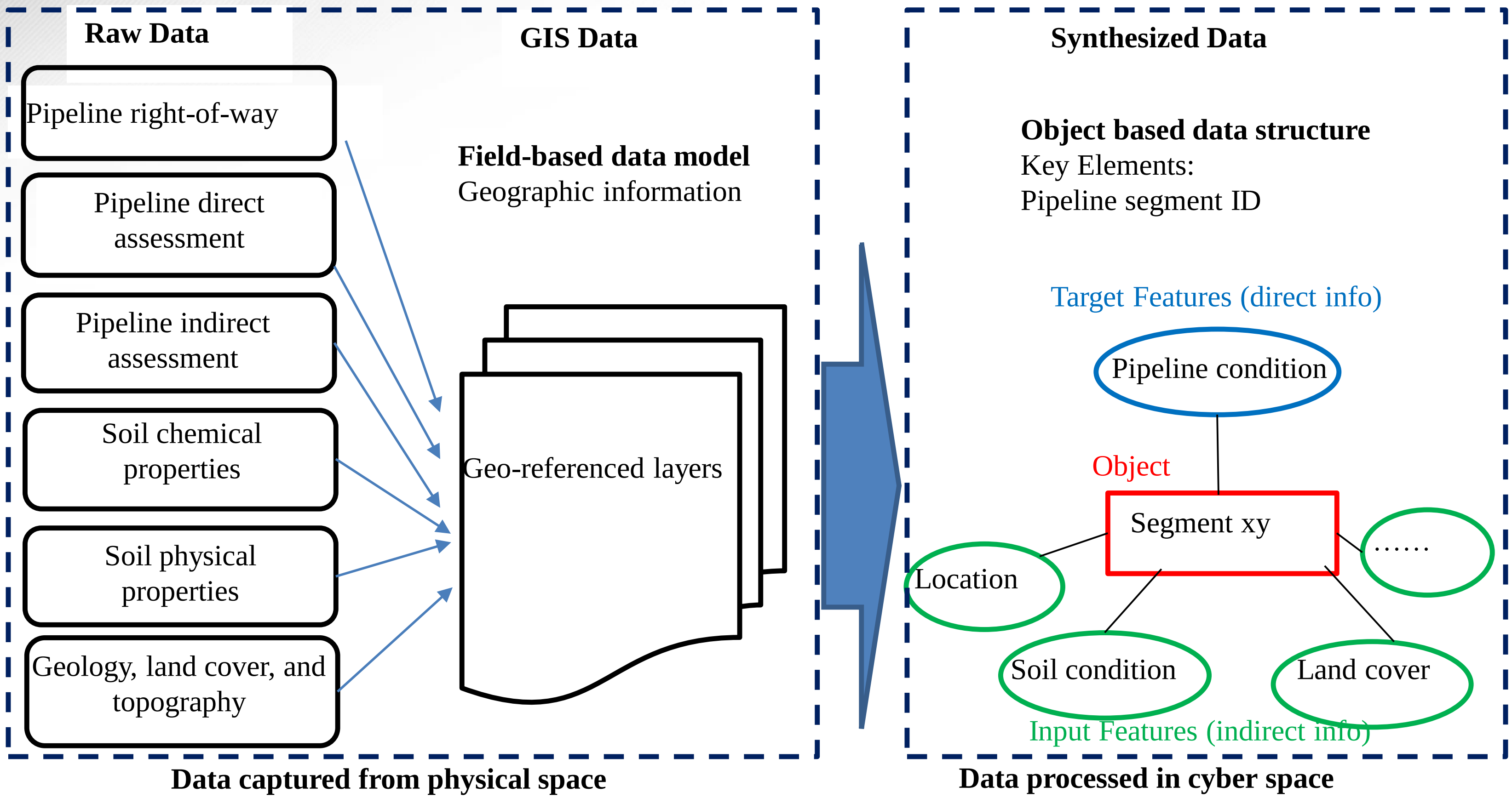






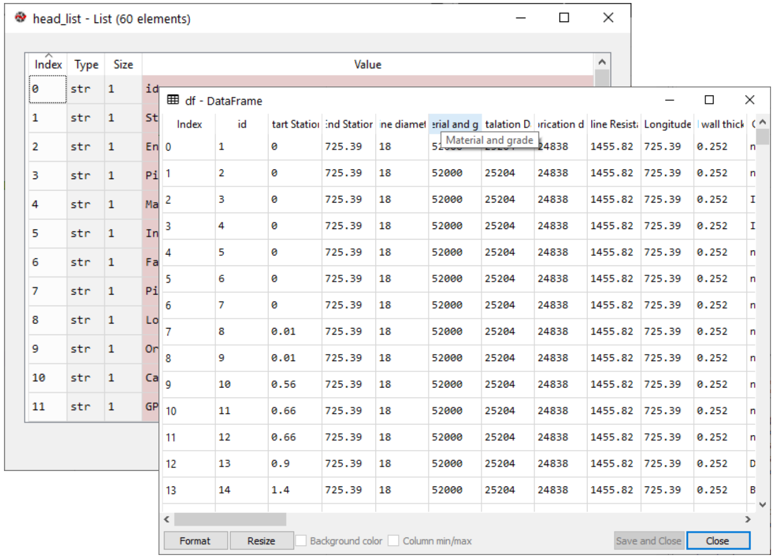
Castaneda et al, NACE 2015

Constructing pipeline segment database



Task 1 continued

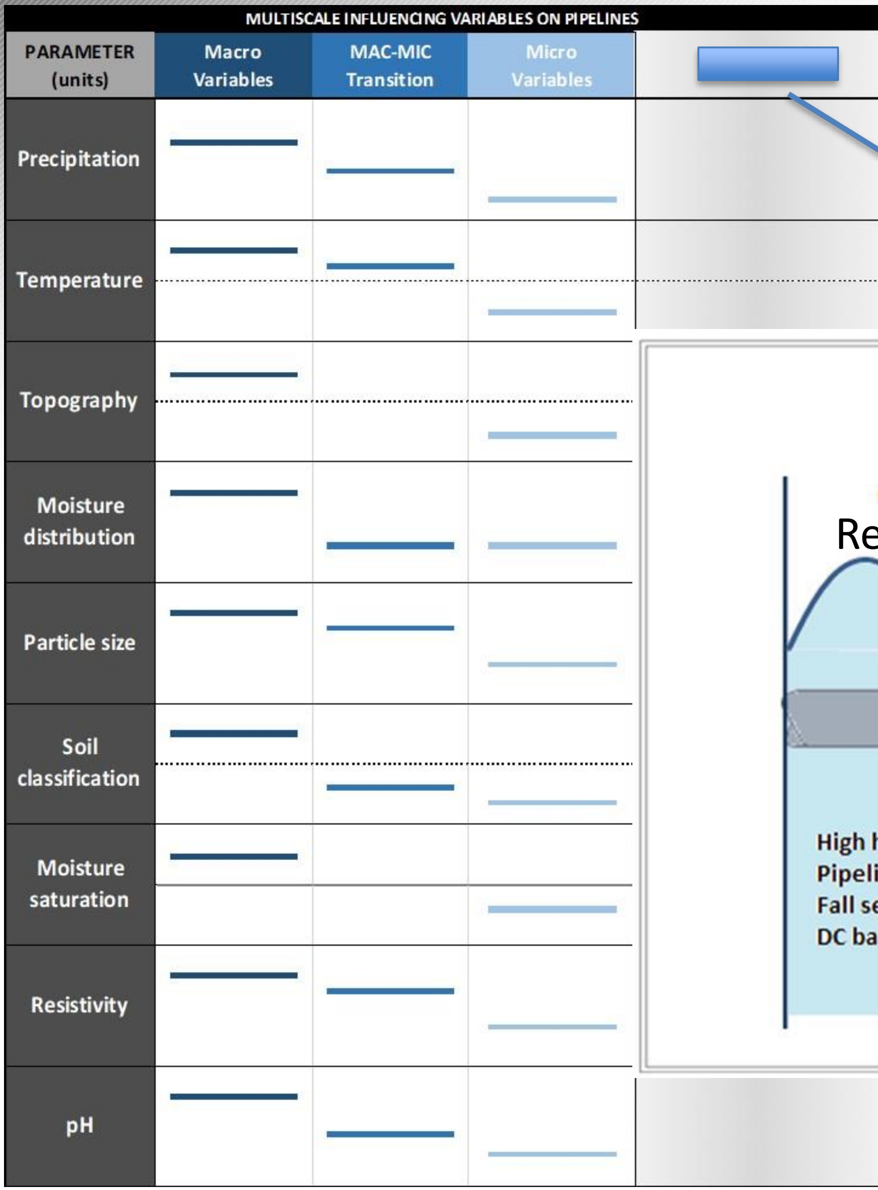
- Pipe_Segment
  - Segment_ID
  - Head mileage number
  - Tail mileage number
  - ILI_data (dataframe)
  - DCVG_data (dataframe)
  - CIS_data (dataframe)
  - Structural_information
  - Corrosion_environment

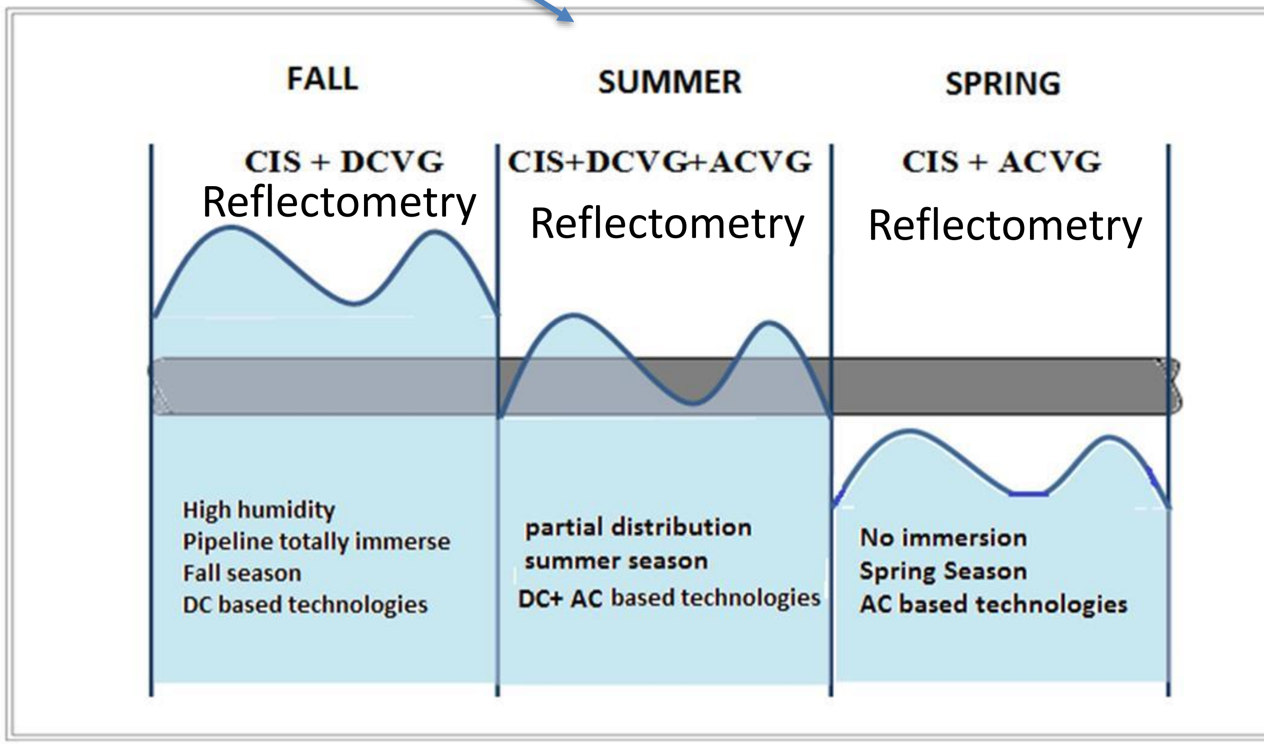


Sample screenshots of the data frame

Application: same segment in different seasons –indirect technologies

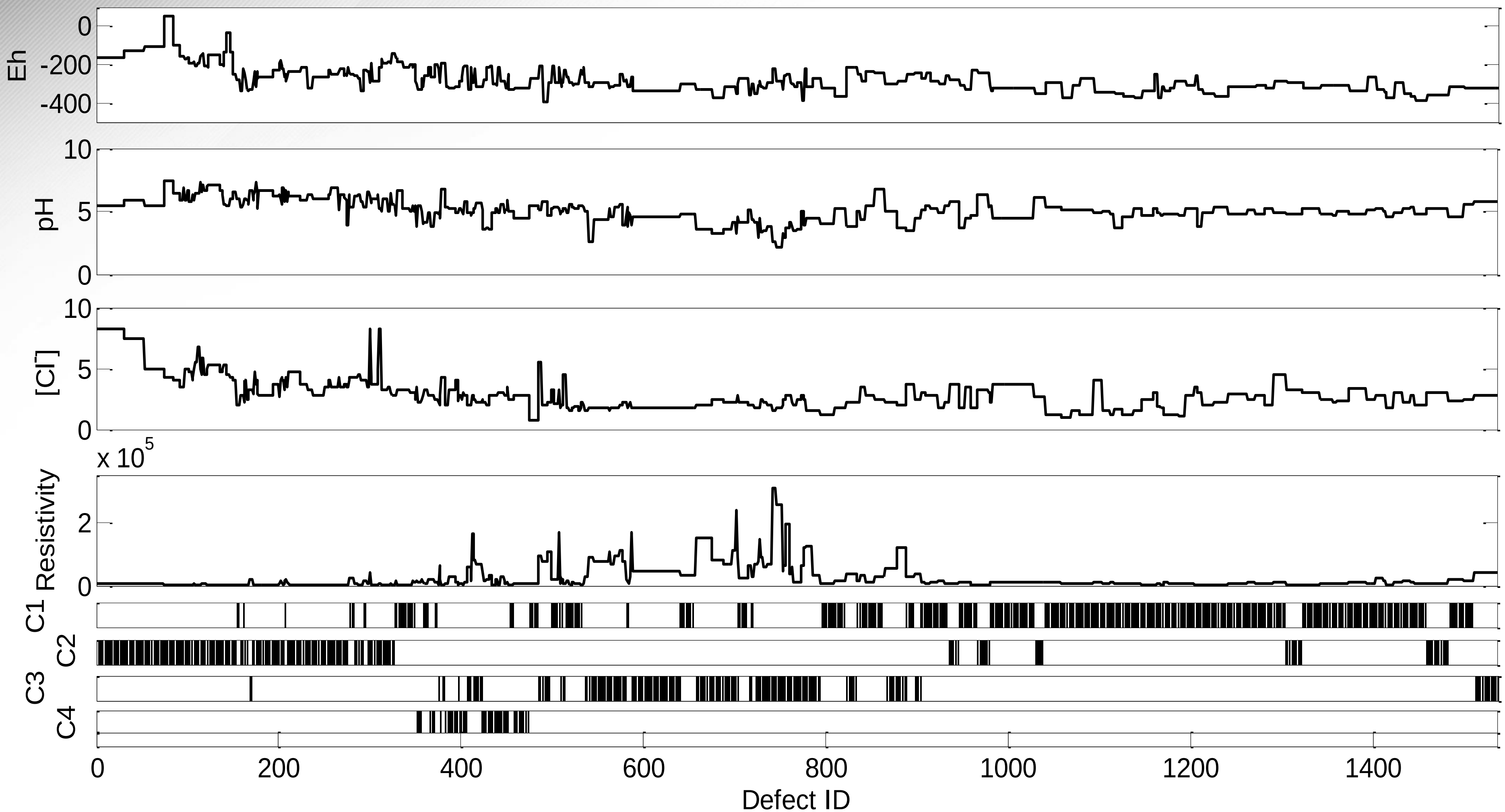
Inspection for maintenance



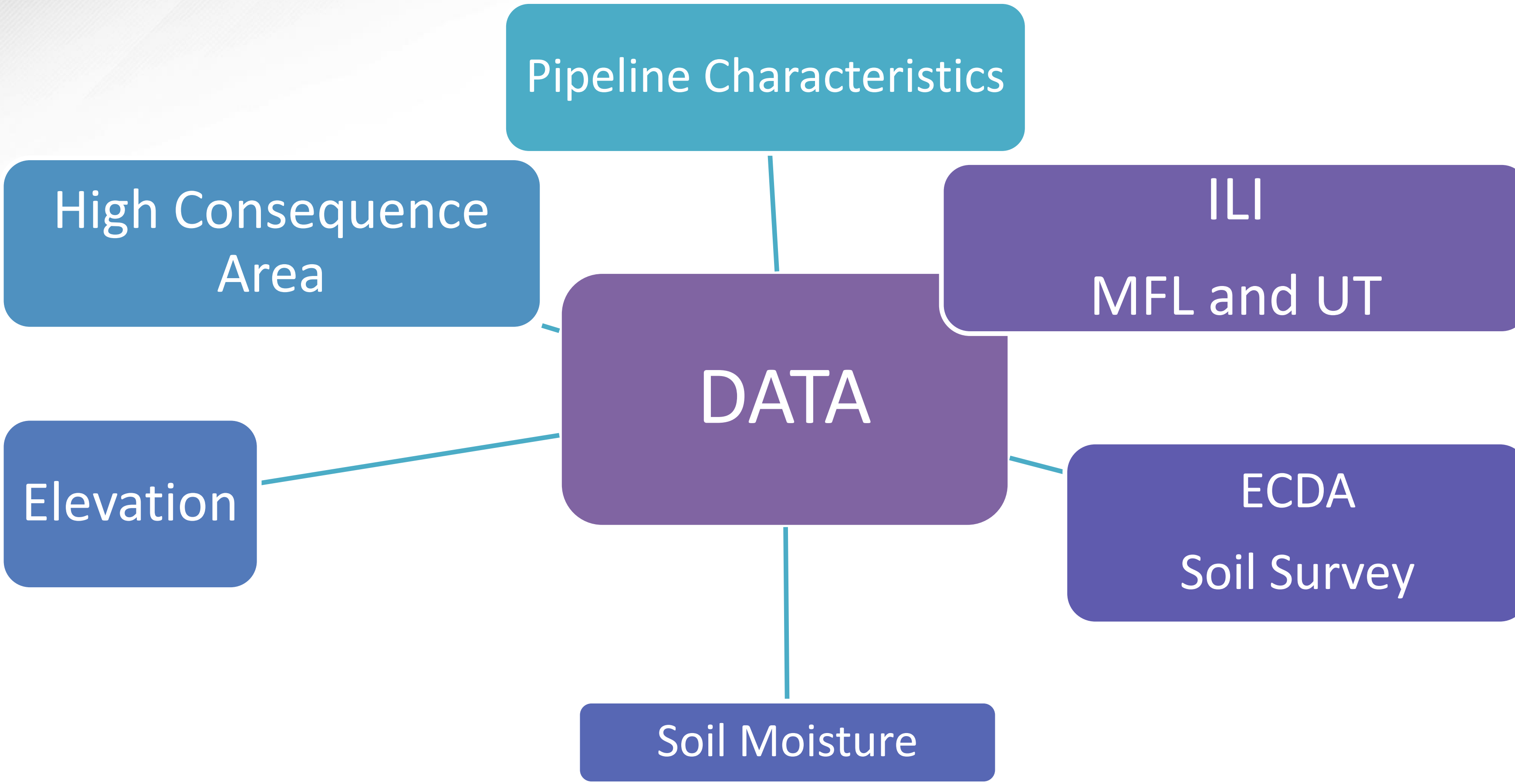


Analysis before direct assessment

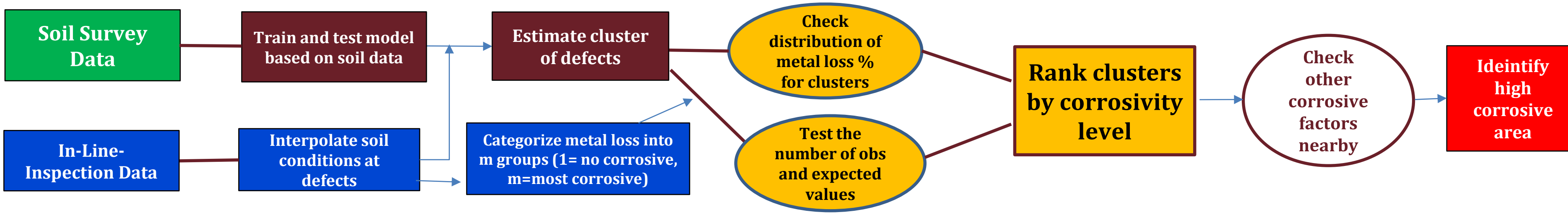
The clustering results



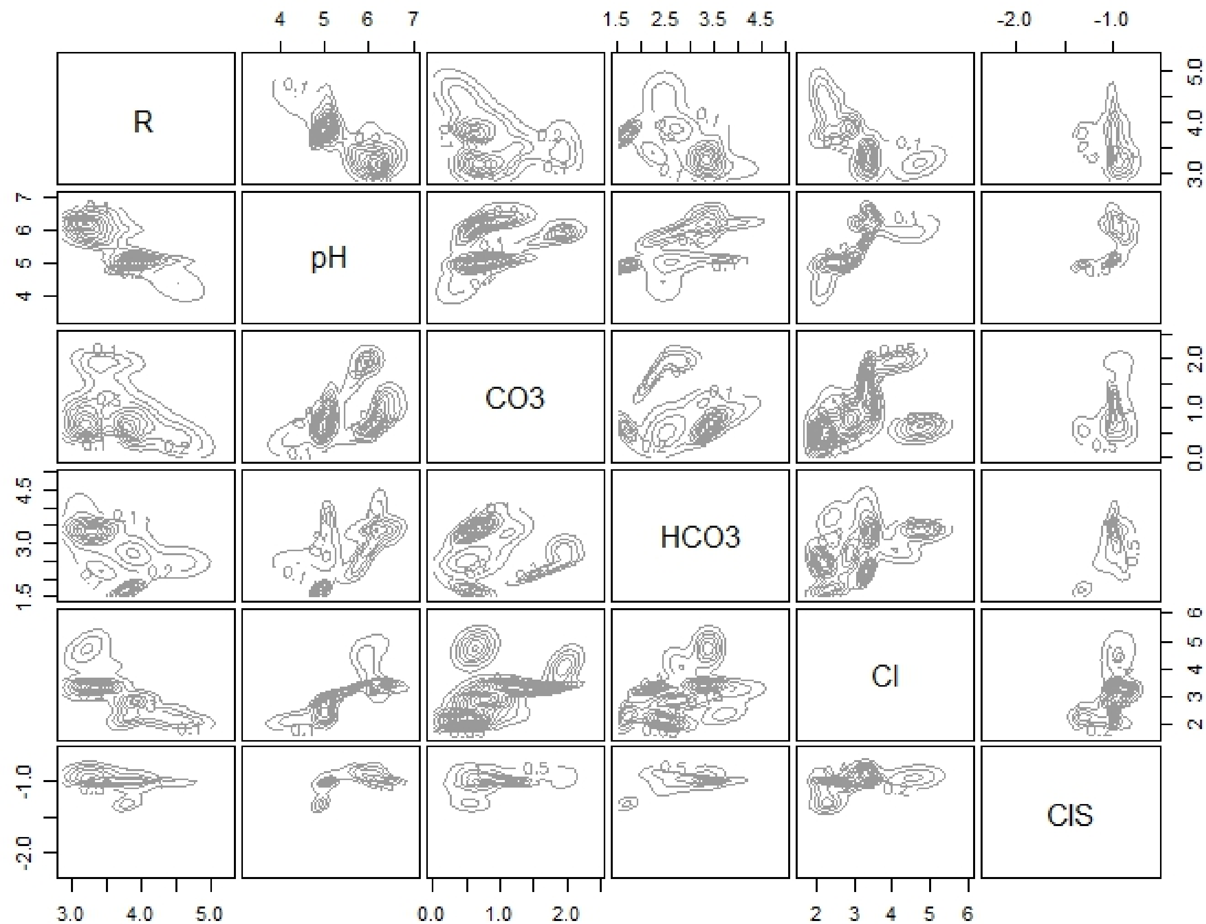
DATA Alignment and Integration



Indirect inspection-Direct Inspection

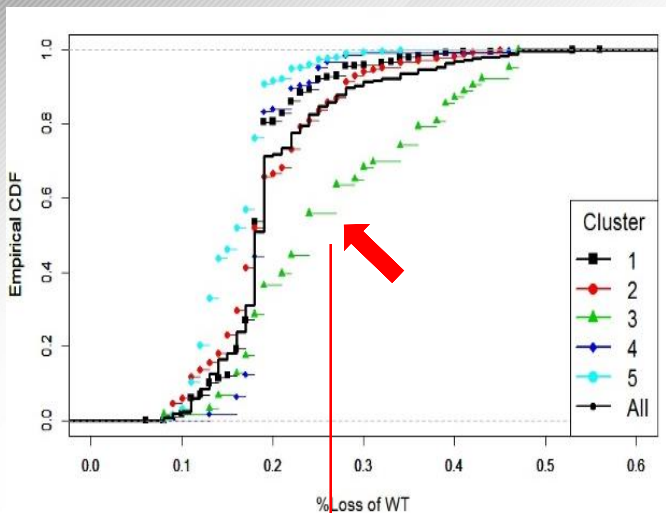


Clusters formation

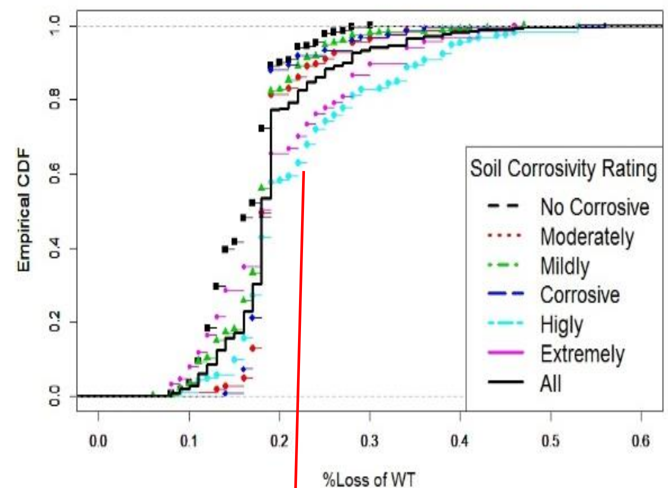


Soil Clustering Result Interpretation

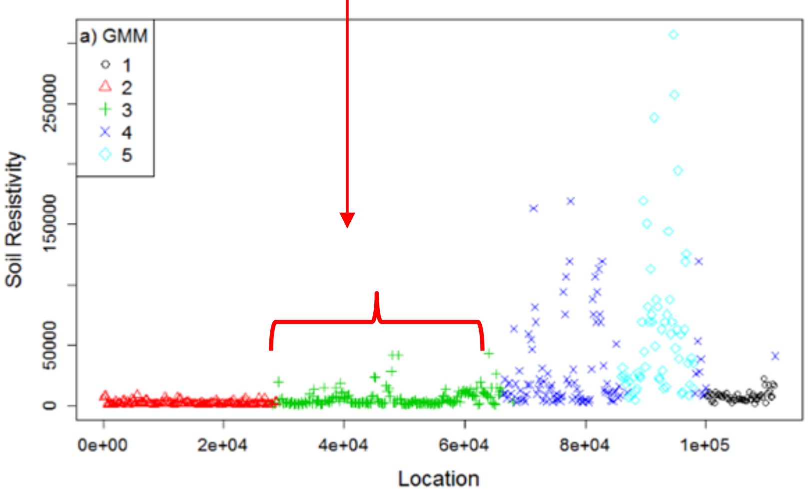
GMM

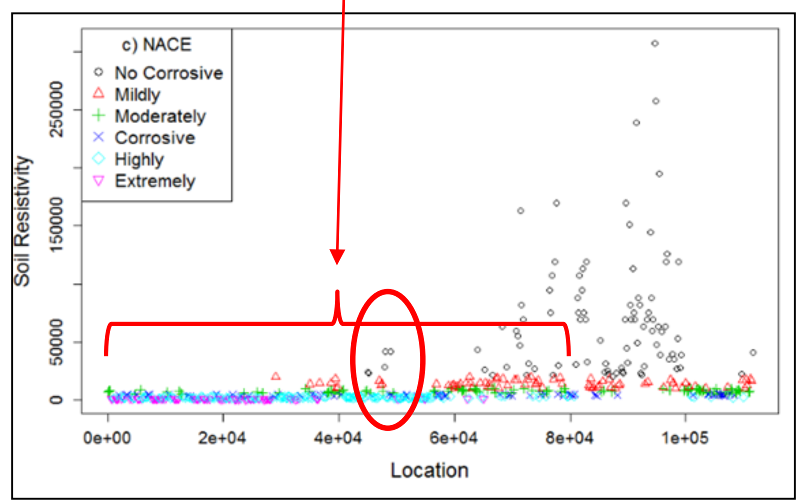


NACE

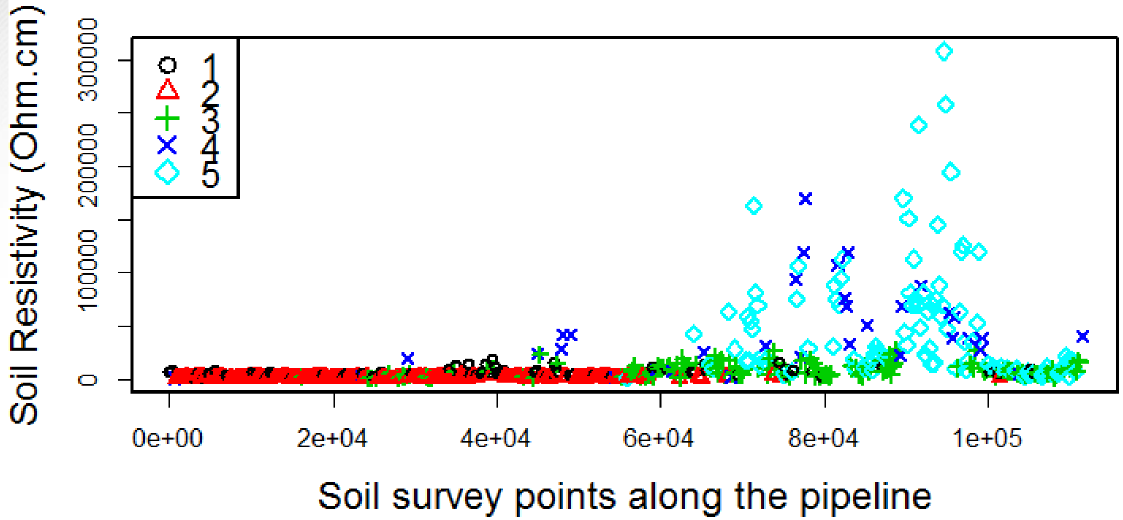


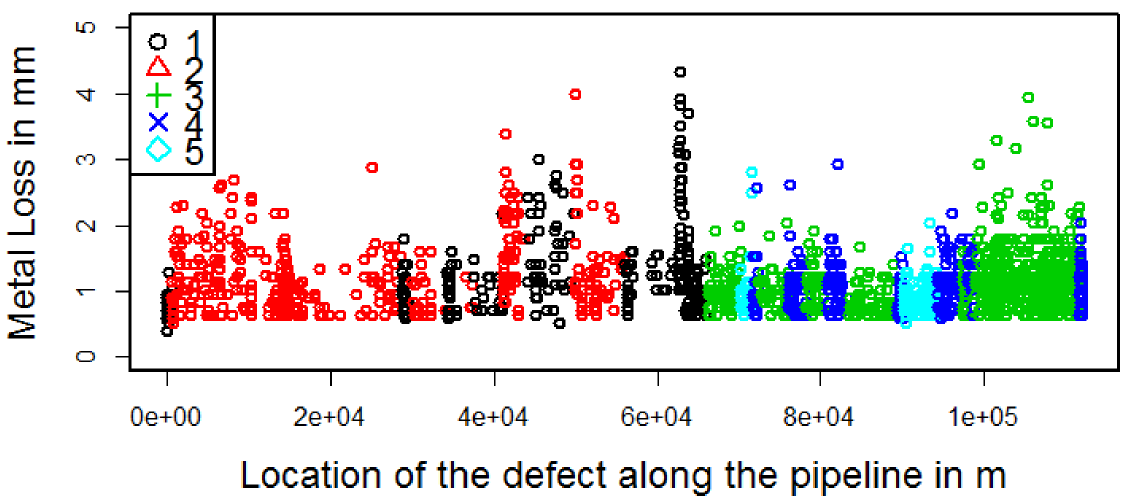
Empirical CDF of % WT loss within clusters



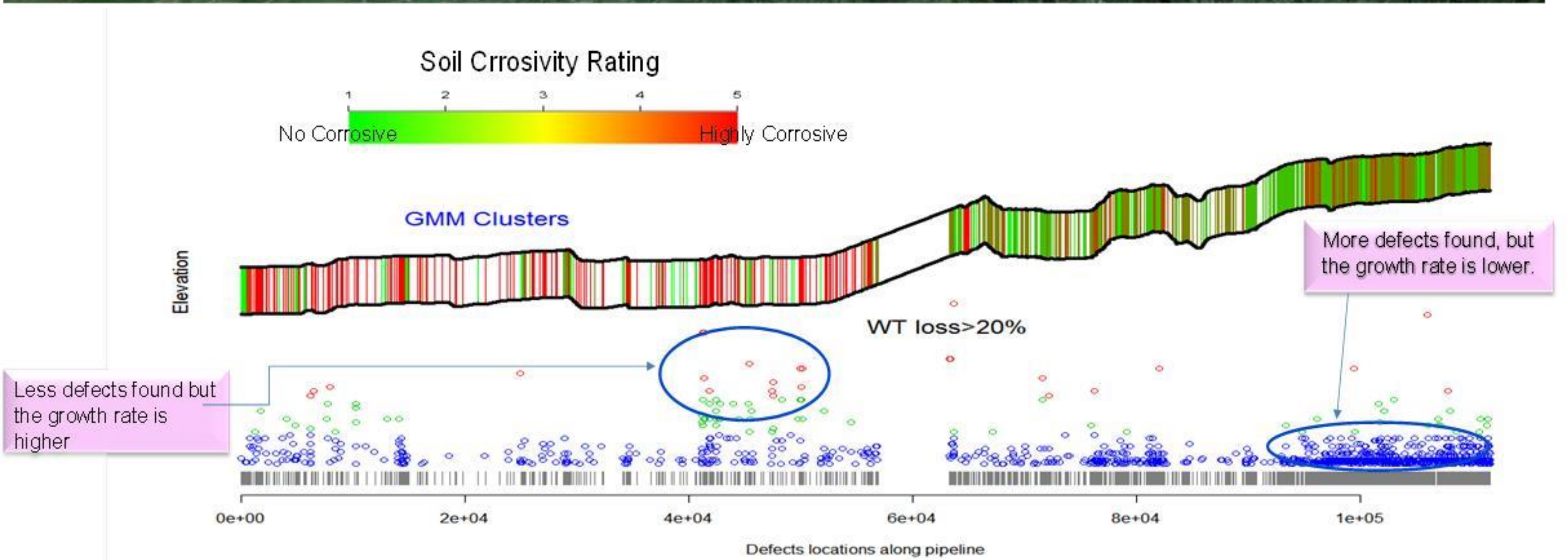


Metal loss vs the location clustered





3D topography location



Reliability Analysis

Probability of failure (or fragility) is defined as the conditional probability of attaining or exceeding prescribed limit states given set of boundary variables.

$$P_f^k(t) = P\{g_k \leq 0 \mid t\}$$

where [gk ≤ 0] = failure event and gk = limit state function for the kth failure mode. Two limit states . Small leak

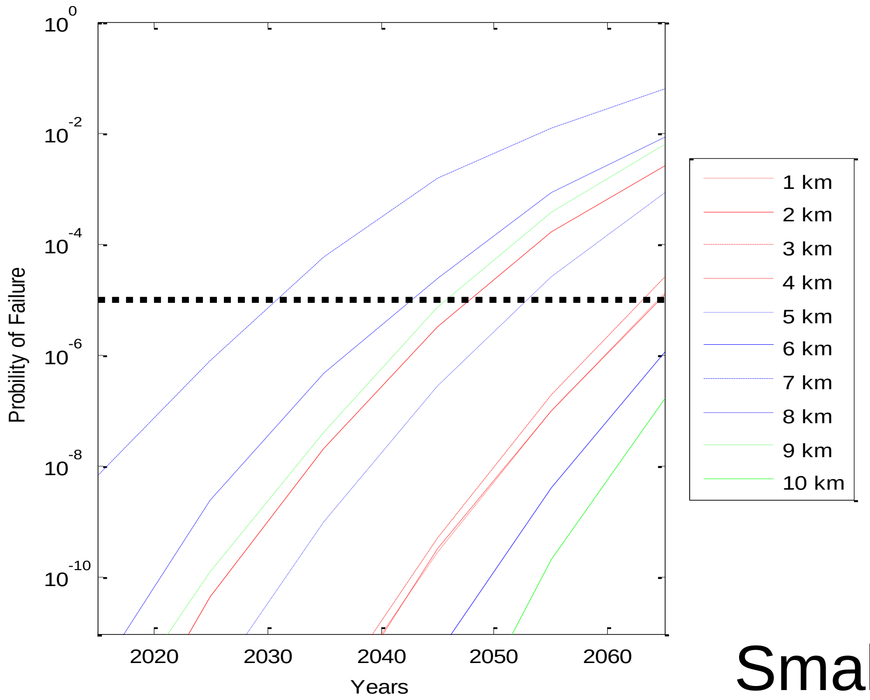
$$g_1 = d_w - d(t)$$

where dw = pipeline wall thickness, and d(t) = the maximum depth of a corrosion defect. For the large leak,

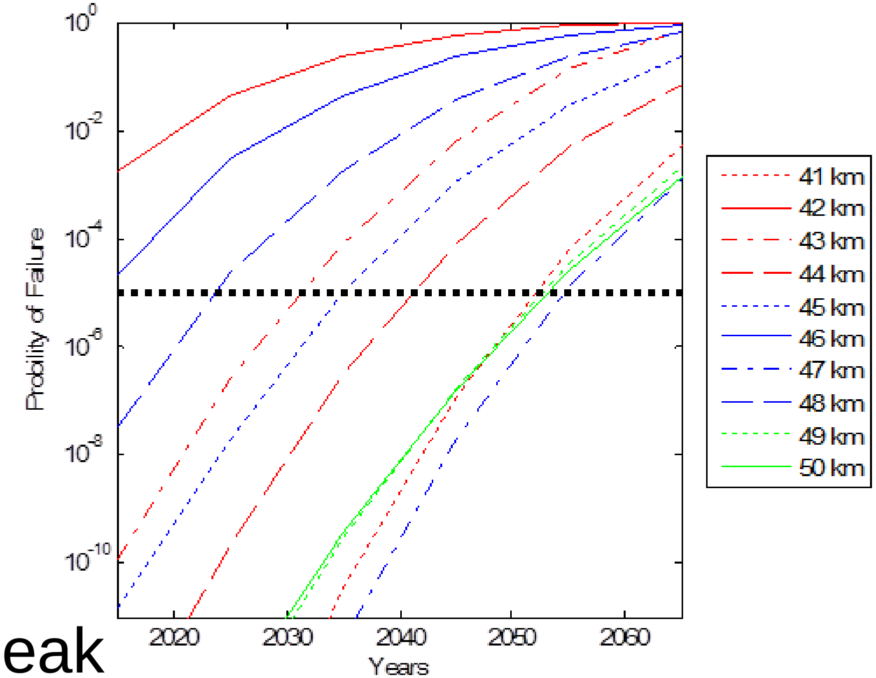
$$g_2 = C_p(t) - D_p$$

where Cp and Dp = pressure resistance and pressure demand, respectively.

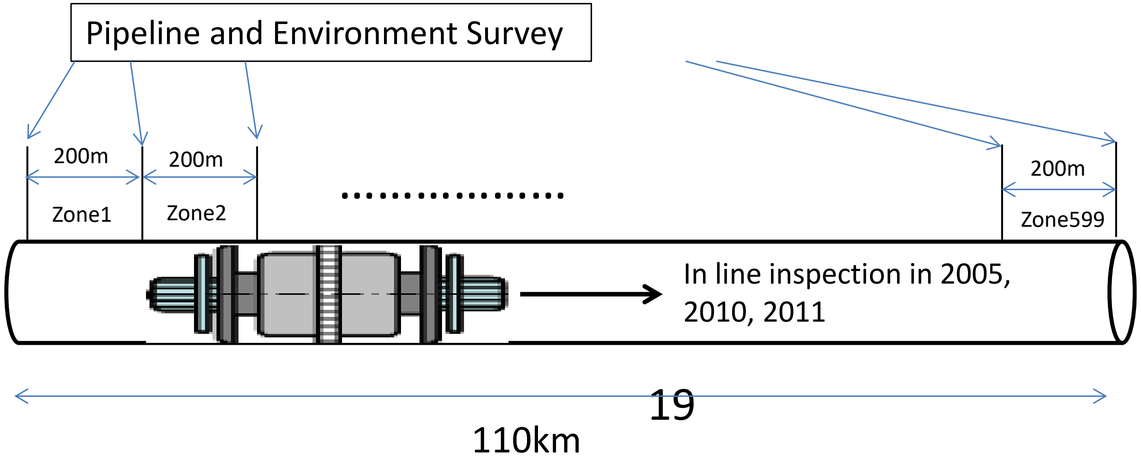
Probability of Failure



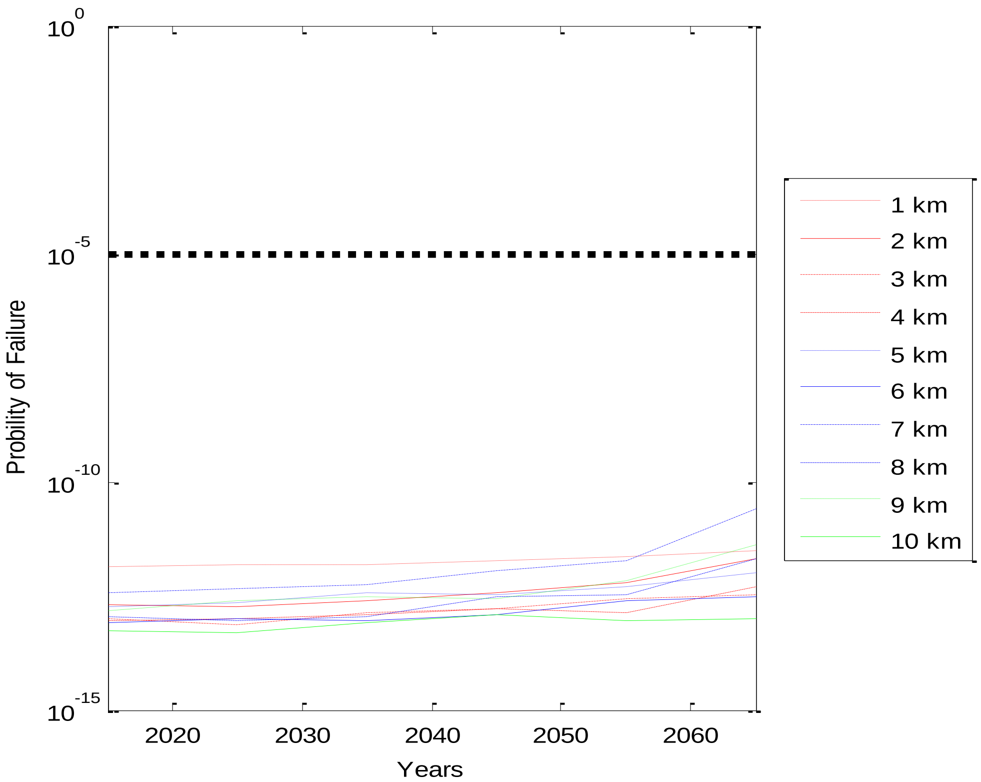
Small leak



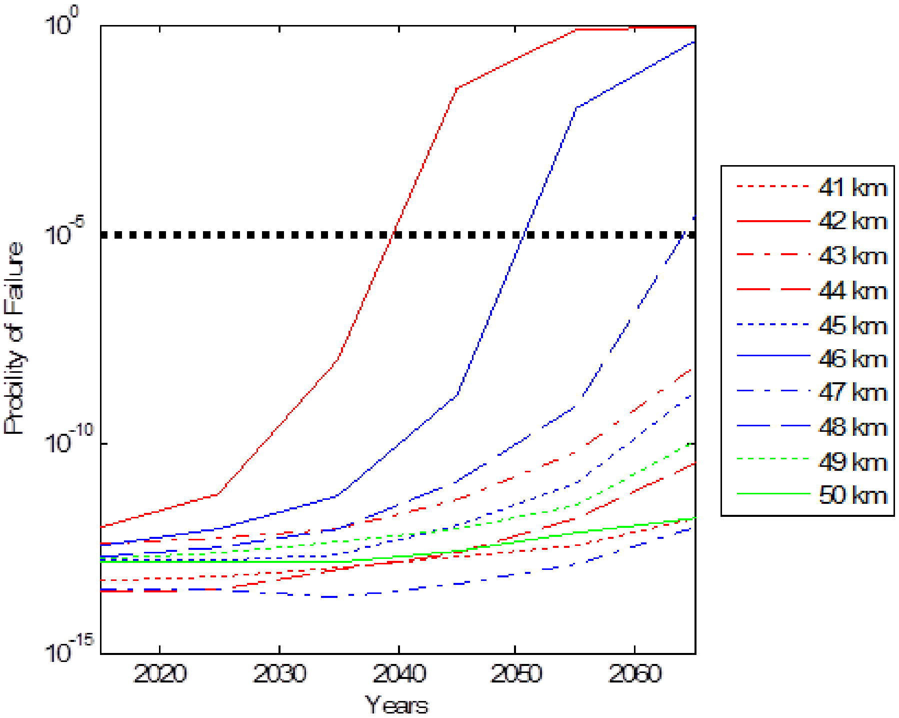
Length	110 km
Diameter	457.20 mm
Wall thickness	6.41 mm
Steel type	API 5L X52
Minimal yielding stress	52 ksi



Probability of Failure



Probability of failure of large leak for 1km to 10km sub-systems with $L/d(t) = 2$



Probability of failure of large leak for 41km to 50km sub-systems with $L/d(t) = 2$

Examples of sites selected based on the methodology

Characterization of the defect and location sites

- Coating defects,
- thickness measurement 0.254 in
- pH=6; resistivity at 1m= 1,948 Ω-cm.

Defect located at 42+ 463.51 km and 42+ 463.61

Characterization of the defect and location sites

- Coating defects,
- thickness measurement 0.254 in
- pH=6; resistivity at 1m= 1,948 Ω-cm.

Defect located at 42+ 459 km and 42+ 461

Defect located at 42+ 459 km and 42+ 461 at 6 oclock

Corrosion pipelines repair Technologies

Table 4 Acceptable Threat Prevention and Repair Methods

Prevention, Detection, and Repair Methods	Third-Party Damage			Corrosion Related		Equipment				Incorrect Operation	Weather Related			Manufacture		Construction				O-Force	Environment
	TPD(IF)	PDP	Vand	Ext	Int	Gask/ Oring	Strip/ BP	Cont/ Rel	Seal/ Pack	IO	CW	L	HR/F	Pipe Seam	Pipe	Gweld	Fab Weld	Coup	WB/B	EM	SCC
Prevention/Detection																					
Aerial patrol	X	X	X	...	...	...	...	...	...	...	X	X	X	...	...	...	...	X	...	X	...
Foot patrol	X	X	X	X	...	...	...	...	...	...	X	X	X	...	...	...	...	X	...	X	...
Visual/mechanical inspection	...	...	...	...	...	X	X	X	X	...	X	...	...	...	...	X	...	...	...	...	...
One-call system	X	X	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Compliance audit	...	...	...	...	...	...	...	...	...	X	...	...	...	...	...	...	...	...	...	...	...
Design specifications	...	...	...	X	X	X	X	X	X	...	...	...	...	...	...	X	...	X	X	X	X
Materials specifications	...	...	...	...	...	X	X	X	X	...	...	...	...	X	X	...	X	...	...	...	...
Manufacturer inspection	...	X	...	...	...	...	...	X	X	...	...	...	...	X	X	...	X	...	...	...	...
Transportation inspection	...	X	...	...	...	...	...	...	...	...	...	...	...	X	X	...	...	...	...	...	...
Construction inspection	...	X	...	...	...	X	X	X	X	...	...	...	...	...	X	X	X	X	X	...	X
Preservice hydrostatic test	...	X	...	...	...	...	...	...	...	...	...	...	...	X	X	X	X	X	X	...	...
Public education	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
O&M procedures	...	X	X	X	X	X	X	X	X	X	X	...	X	...	...	...	...	X	X	X	X
Operator training	...	...	...	...	...	...	...	...	...	X	...	...	...	...	...	...	...	...	...	...	...
Increase marker frequency	X	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Strain monitoring	...	...	...	...	...	...	...	...	...	...	...	...	X	...	...	...	...	...	...	X	...
External protection	X	X	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	X	...
Maintain ROW	X	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	X	...
Increased wall thickness	X	X	X	X	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	X	...
Warning tape mesh	X	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
CP monitor/maintain	...	...	...	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	X
Internal cleaning	...	...	...	...	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Leakage control measures	...	X	X	X	X	X	X	X	X	...	...	...	...	...	...	...	...	X	...	...	...
Pig-GPS/strain measurement	...	...	...	...	...	...	...	...	...	...	X	...	X	...	...	...	...	...	...	X	...
Reduce external stress	...	...	...	...	...	...	X	...	...	...	...	...	...	...	...	...	...	X	X	X	X
Install heat tracing	...	...	...	...	...	...	...	...	...	...	X	...	...	...	...	...	...	...	...	...	...
Line relocation	X	...	X	...	...	...	...	...	...	...	X	...	X	...	...	...	...	...	...	X	...
Rehabilitation	...	X	...	X	X	...	...	...	...	...	...	...	...	...	...	...	...	X	X	X	X
Coating repair	...	...	...	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	X
Increase cover depth	X	...	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	X	...	...
Operating temperature reduction	...	...	...	...	...	X	...	...	X	...	...	...	...	...	...	...	...	...	...	...	X
Reduce moisture	...	...	...	...	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Biocide/inhibiting injection	...	...	...	...	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Install thermal protection	...	...	...	...	...	...	...	...	...	...	X	...	...	...	...	...	...	...	...	...	...

www. standards

Table 4 Acceptable Threat Prevention and Repair Methods (Cont'd)

Prevention, Detection, and Repair Methods	Third-Party Damage			Corrosion Related		Equipment				Incorrect Operation	Weather Related			Manufacture		Construction				O-Force	Environ ment
	TPD(IF)	PDP	Vand	Ext	Int	Gask/ Oring	Strip/ BP	Cont/ Rel	Seal/ Pack	IO	CW	L	HR/F	Pipe Seam	Pipe	Gweld	Fab Weld	Coup	WB/B	EM	SCC
Repairs																					
Pressure reduction	...	X	...	X	X	...	...	...	...	...	...	...	...	X	X	X	X	X	...	...	X
Replacement	...	X	X	X	X	X	X	X	X	...	X	X	X	X	X	X	X	X	X	X	X
ECA, recoat	...	...	...	X	X	...	...	...	...	...	...	...	...	...	...	X	...	...	...	...	...
Grind repair/ECA	...	X	X	...	...	...	...	...	...	...	...	...	...	X	X	X	X	...	...	...	X
Direct deposition weld	...	...	X	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Type B, pressurized sleeve	...	X	X	X	X	...	...	...	...	...	...	...	...	X	X	...	X	X	...	...	X
Type A, reinforcing sleeve	...	X	X	X	...	...	...	...	...	...	...	...	...	X	X	...	...	...	...	...	X
Composite sleeve	...	...	...	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Epoxy filled sleeve	...	X	X	X	...	...	...	...	...	...	...	...	...	X	X	X	X	X	X	...	...
Mechanical leak clamp	...	...	...	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Cont/Rel = Control/Relief Equipment Malfunction
Coup = Coupling Failure
CW = Cold Weather
EM = Earth Movement
Ext = External Corrosion
Fab Weld = Defective Fabrication Weld
Gask/Oring = Gasket or O-Ring
Gweld = Defective Pipe Girth Weld
HR/F = Heavy Rains or Floods
Int = Internal Corrosion
IO = Incorrect Operations Company Procedure
L = Lightning
PDP = Previously Damaged Pipe (delayed failure mode)
Pipe = Defective Pipe
Pipe Seam = Defective Pipe Seam
SCC = Stress Corrosion Cracking
Seal/Pack = Seal/Pump Packing Failure
Strip/BP = Stripped Thread/Broken Pipe
TPD(IF) = Damage Inflicted by First, Second, or Third Parties
Vand = Vandalism
WB/B = Wrinkle Bend or Buckle

Repairing and Maintenance Inspection intervals

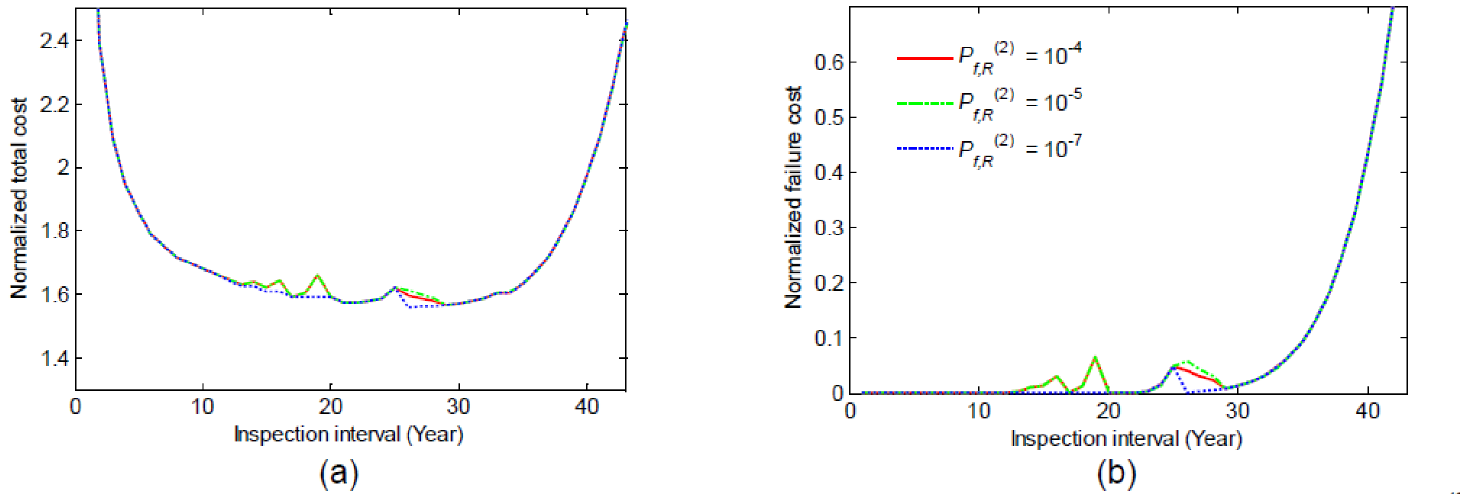


Figure 6: Normalized (a) total cost, (b) failure cost for different Δt_{insp} considering different $P_{f,R}^{(2)}$

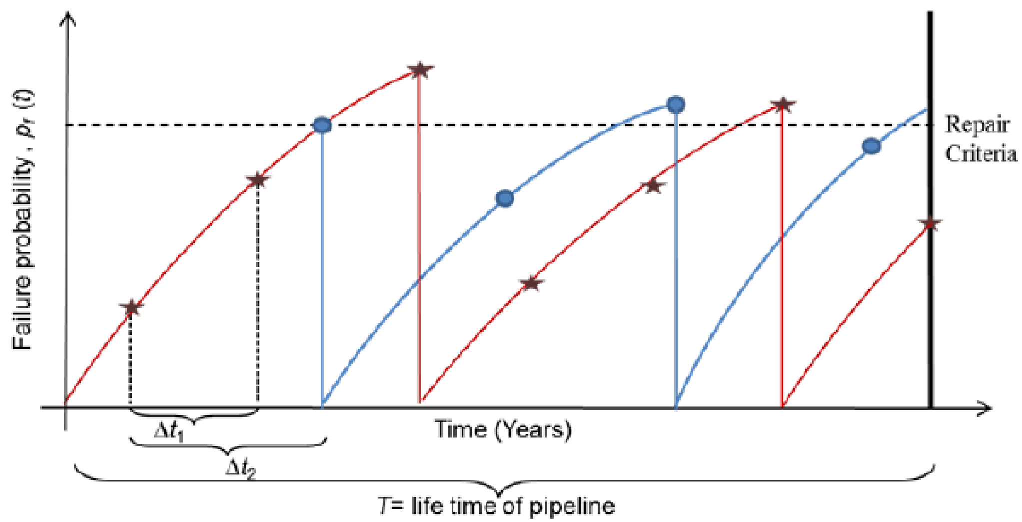
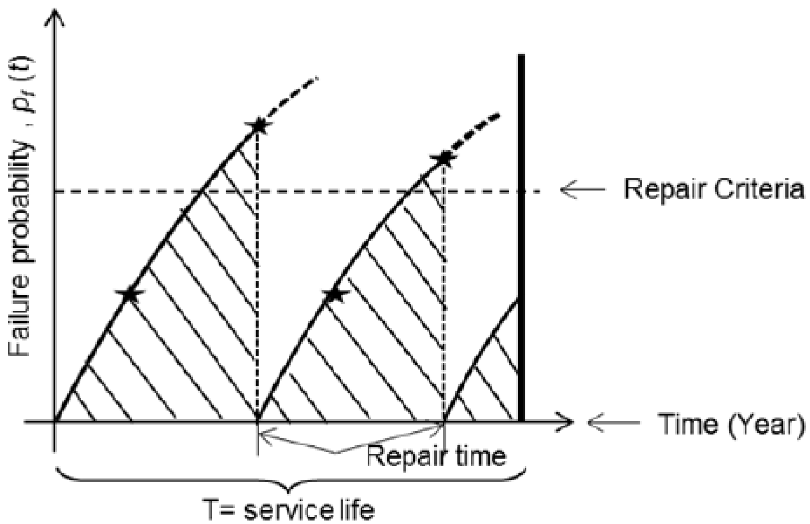


Figure 7: Comparison $\overline{P}_{f,i}^{(k)}$ for two inspection intervals (star: Δt_1, circle: Δt_2)



Failure probability updated
after repair
Incorporating area
underneath the curve

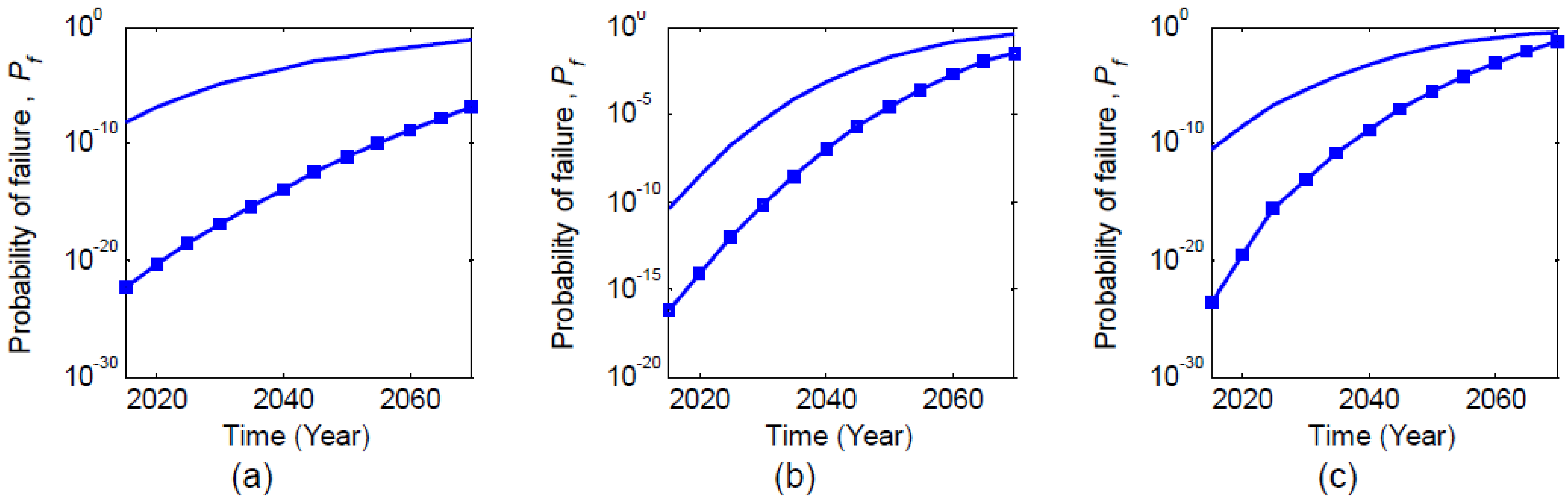
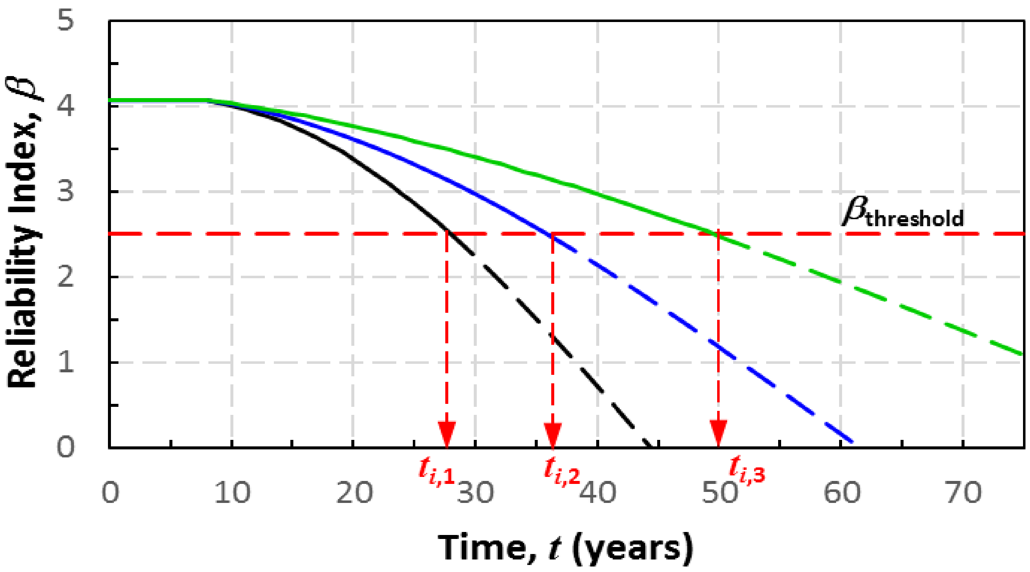
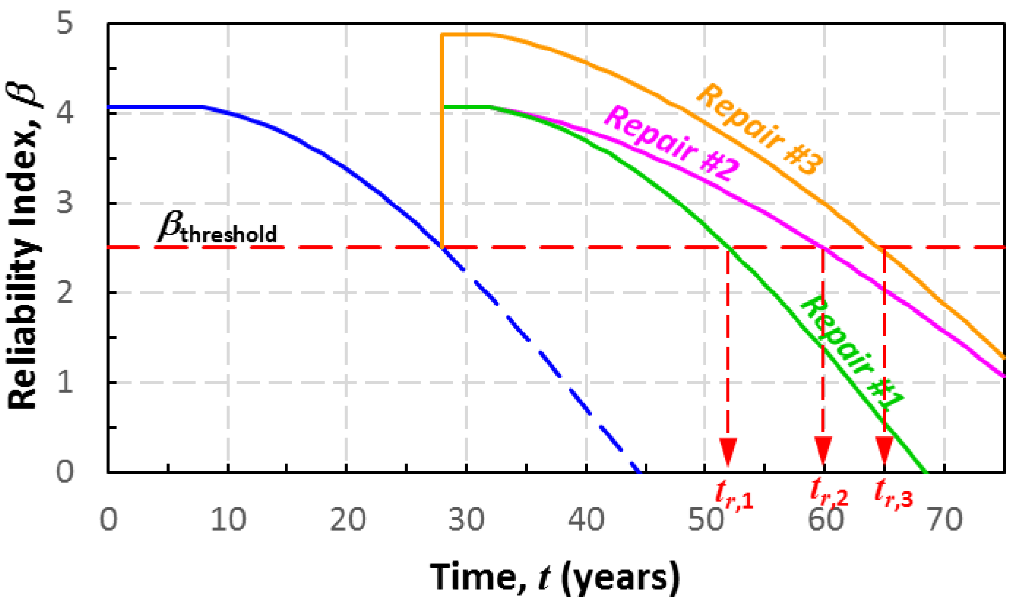


Figure 2: Time-dependent failure probabilities associated with scenarios I (solid lines) and II (marked lines) for (a) small leak, (b) large leak and (c) rupture failure modes

Unification of modeling with integrity





Effect of different intervention strategies on expected service life

Summary and Conclusions

- Based on the analysis of data in the case study, it was concluded that the clustering approach can accurately estimate the severity of soil corrosiveness severity. It is also more flexible in terms of the range of the factors it can incorporate. Instead of categorizing the factors at within certain ranges, it considers the distributions of the environmental factors and the correlations between those factors.

- The data alignment from field filed measurements can mislead the characterization (or severity) of defect indications along the right of way. Data treatment influences the data reliability and robustness.

- Modeling the corrosion rate using environmental factors is very complex because of many unknown factors. Nevertheless, we intended to connect the environmental corrosivity to the metal loss rate by using statistical approach.

- We could prioritize the number of indications based on parameters that relate the corrosion mechanisms, the total number of characterization selected sites were less than 1% from the ILI and indirect measurements and results.

Thanks to our corrosion group

Yenny Cubides From Colombia

Sponsors for the NCMRL

Shell

FREEPORT-McMoRAN

ExxonMobil

Chevron

ConocoPhillips

BAKER HUGHES
a GE company

ComEd
An Exelon Company

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TOYOTA

BASF
We create chemistry

HYUNDAI

HYUNDAI STEEL

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