**CAAP Quarterly Report**

**1/15/2025**

*Project Name: Pipeline Risk Management Using Artificial Intelligence-Enabled Modeling and Decision Making*

*Contract Number: 693JK32150001CAAP*

*Prime University: Rutgers University*

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*Reporting Period: 10/1/2024 – 12/31/2024*

**Project Activities for Reporting Period:**

*Task 1 Literature Review (Completed)*

*Task 2 Data Collection from Industry Partners (Completed)*

*Task 3 Data-Driven Probabilistic Modeling of Pipeline Defects (Completed)*

*Task 4 Quantification of Probability of Failure (Completed)*

*Task 5 Decision Making of Inspection and Repair Strategy using Reinforcement Learning*

The reinforcement learning model was refined to include the corrosion growth prediction from the developed BNN model for decision making. Based on that, case studies were conducted to find the optimum maintenance strategy as the soil properties vary. The ILI data and soil properties from the Mexico pipeline are used in the analysis. The transmission pipeline is made of grade X52 steel, with a total length of 112 km. The outside diameter of 457.2 mm and the wall thickness is 6.4 mm.

***Analysis Scenarios***

It has been found that soil properties especially moisture are important influencing factors for steel pipeline corrosion. Therefore, to assess its impact on corrosion growth, four scenarios having low and high soil moisture values were selected, while using the average values of other soil properties. Also, scenario 4 was selected to evaluate the corrosion growth in high corrosive soil zone. The soil properties in four scenarios are detailed in Table 1.

**Table 1** Four scenarios with different soil properties to predict corrosion growth

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Input variables | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
| Elevation (m) | 1266.25 | 1266.25 | 1266.25 | 247 |
| Eh (mV) | -268.59 | -268.59 | -268.59 | -235.00 |
| Resistivity\_1m (Ω) | 22235 | 22235 | 22235 | 7540 |
| Resistivity\_2m (Ω) | 26243 | 2624 | 26243 | 37699 |
| pH | 5.19 | 5.19 | 5.19 | 6.57 |
| CO32- (mol/L) | 0.82 | 0.82 | 0.82 | 1.892 |
| HCO3- (mol/L) | 2.72 | 2.72 | 2.72 | 1.72 |
| Cl- (mol/L) | 3.05 | 3.05 | 3.05 | 3.5 |
| SO42- (mol/L) | 0.0994 | 0.0994 | 0.0994 | 0.216 |
| Soil moisture | 0.27 | 0.24 | 0.29 | 0.2776 |
| Soil type | 5 | 5 | 5 | 3 |

***Life-Cycle Cost***

The life-cycle cost function considers both repair costs and failure costs, expressed in Eq. (1). The repair cost includes expenses for composite wrap and pipe replacement, which are incurred when the corresponding maintenance actions are implemented. The failure cost accounts for the consequences of leakage and rupture failures in each year. To reflect the time value of money, an annual discount rate of 3% is used. By discounting future costs of repair and failure costs to the present values, the more reasonable economic evaluation over the analysis period can be obtained.

 (1)

where, *ns* is the number of times the composite wrap is used; *Cs* is the composite wrap cost; *r* is the annual discount rate, which is 0.03 in this case; *tsi* is the year when *ith* composite wrap repair occurs; *nr* is the number of times the replacement is used; *Cr* is the replacement cost; *trj* is the year when *jth* replacement occurs; Δ*Pli*is the is the incremental leakage failure probability in year *i*; *Cl* is the leakage failure cost; Δ*Pbi*is the is the incremental rupture failure probability in year *j*; *Cb* is the rupture failure cost.

For pipeline repair with composite wrap, it provides additional structural protection by increasing wall thickness and burst pressure. Furthermore, it is assumed that the subsequent corrosion growth rate in future years slows down by 50% after composite wrap, reflecting the improved resistance to corrosion due to the isolation of pipe wall from soil. For pipeline replacement, corrosion defect is reset to zero, as a new pipeline segment is installed. Corrosion growth is then recalculated starting from the year of replacement.

It is expected that the pipe repair and replacement costs vary with pipe diameter and length. Based on the cost data compiled in the previous PHMSA report (1), the estimated cost is $9,843 for composite wrap, and $42,651 for replacement for the pipe segment with 18-inch diameter and 3.28-ft length. These cost parameters will be updated later for sensitivity analysis. Based on the comprehensive database of incidents from PHMSA, it has been found that the average rupture failure cost for gas transmission and gathering pipelines is $396,261. As reported by Gomes and Beck [2], the small leakage failure cost is about 0.1% -1% of rupture failure cost. Therefore, the leakage failure cost is assumed to be 1% of the rupture failure cost, $3,963.

**Reinforcement Learning Algorithm**

To determine the optimized maintenance plan for each scenario, the reinforcement learning (RL) integrated by BNN-based corrosion growth model was used. The integrated methodology begins by training separate BNN models for prediction corrosion depth and length influenced by soil properties, where each BNN outputs has a predictive distribution rather than a single deterministic prediction. Once trained, these BNN models are employed to generate multi-year predictions of mean and standard deviation for both corrosion depth and length. The BNN model captures the aleatoric and epistemic uncertainty in the corrosion process by sampling from the learned distributions over a range of future time steps. Then, a DQN agent in RL uses these corrosion curves to simulate each maintenance decision, such as installing composite wrap or replacing a pipe segment at different years.

Within each year of simulation, the RL environment retrieves the BNN-based corrosion estimates (mean and standard deviation) for that specific year to calculate the incremental probability of failure under different decision actions. These probabilities, along with the associated maintenance or failure costs, define the RL reward function. The reward function is then defined as the negative of the cost function, ensuring that the RL agent is incentivized to minimize total costs while balancing maintenance and failure risks. Over multiple training episodes, the DQN learns an optimal or near-optimal policy for minimizing expected total cost while keeping risk below a specified threshold. This approach thus combines the probabilistic modeling of BNN with the adaptive decision-making capability of reinforcement learning, yielding a proactive pipeline maintenance strategy that accounts for uncertainty in future corrosion evolution.

**Preliminary Results**

The preliminary results of optimized maintenance strategy at four selected scenarios are compared in Table 2. The results of maintenance strategy in four scenarios demonstrate that the impact of soil properties on pipeline corrosion growth and associated maintenance costs. Scenario 1 resulted in a total cost of $7,544 with a maintenance action implemented in year 8, suggesting moderate corrosion growth requiring an intervention earlier than Scenario 2. In Scenario 2, where soil moisture content was the lowest at 0.24, the total cost was reduced to $5,955, and the maintenance action was delayed to year 16. This indicates that lower soil moisture slows down corrosion, reducing both failure risk and maintenance frequency. Scenario 3 resulted in the higher cost of $7,770 and an earlier intervention at year 7, reflecting accelerated corrosion under higher moisture conditions. It highlights that soil moisture influences the timing and cost-effectiveness of maintenance strategies, with higher moisture levels leading to earlier interventions due to increased corrosion. On the other hand, Scenario 4, representing the most severe corrosion conditions, requires two maintenance actions, one in year 3 and another in year 47, resulting in a total cost of $11,128.

Table 2 Comparison of RL-based maintenance plan for four selected scenarios

|  |  |  |  |
| --- | --- | --- | --- |
| Scenarios | Maintenance plan | Total cost ($) | Pf threshold |
| 1 | [8, composite wrap] | 7,544 | Pass |
| 2 | [16, composite wrap] | 5,955 | Pass |
| 3 | [7, composite wrap] | 7,770 | Pass |
| 4 | [3, composite wrap], [47, composite wrap] | 11,128 | Pass |

Table 3 compares RL-based maintenance strategy with randomly generated plans in terms of maintenance timing, actions, and associated costs. The results demonstrate that performing maintenance earlier than the RL-based plan (Random #1) results in higher total costs due to unnecessary early interventions. In contrast, delaying maintenance beyond the RL-scheduled timing (Random #2) increases the probability of failure, leading to higher failure costs. These findings prove that the RL-based plan outperforms random strategies by effectively balancing repair costs and failure risks.

Table 3Comparison between RL-based and random maintenance strategies

|  |  |  |  |
| --- | --- | --- | --- |
| Scenarios | Maintenance plan | Total cost ($) | Pf threshold |
| 1 | RL | [8, composite wrap] | 7543.84 | Pass |
| Random #1 | [7, composite wrap] | 7937.14 | Pass |
| Random #2 | [11, composite wrap] | 10345.54 | Fail (0.011) |
| 2 | RL | [16, composite wrap] | 5955.43 | Pass |
| Random #1 | [10, composite wrap] | 7110.79 | Pass  |
| Random #2 | [19, composite wrap] | 17596.18 | Fail (0.053) |
| 3 | RL | [7, composite wrap] | 7770.16 | Pass |
| Random #1 | [4, composite wrap] | 8490.66 | Pass  |
| Random #2 | [13, composite wrap] | 54818.79 | Fail (0.178) |
| 4 | RL | [3, composite wrap], [47, composite wrap] | 11127.73 | Pass |
| Random #1 | [2, composite wrap], [21, composite wrap] | 14145.10 | Pass  |
| Random #2 | [7, composite wrap], [44, composite wrap] | 60024.18 | Fail (0.157) |

# References:

1. International, I., *Cost and Benefit Impact Analysis of the PHMSA Natural Gas Gathering and Transmission Safety Regulation Proposal*. 2016.

2. Gomes, W.J. and A.T. Beck, *Optimal inspection and design of onshore pipelines under external corrosion process.* Structural Safety, 2014. 47: p. 48-58.

**Project Activities with Cost Share Partners:**

Cost share is provided by Rutgers University and Marquette University during this quarterly period as budgeted in the proposal.

**Project Activities with External Partners:**

N/A

**Potential Project Risks:**

N/A

**Future Project Work:**

Work will be continued on Task 5 on decision making of inspection timing and repair strategy.

**Potential Impacts to Pipeline Safety:**

The AI-enabled modeling and analysis of pipeline inspection data will be used to develop probabilistic growth models of corrosion defects and make cost-effective repair or replacement decisions to minimize pipeline failure risk.