**CAAP 1st Annual Report**

**Date of Report**: *10/06/2024*

**Prepared for**: *U.S. DOT Pipeline and Hazardous Materials Safety Administration*

**Annual Period: From** *9/30/2023* **to** *9/30/2024*

**Contract Number**: *693JK32050008CAAP*

**Project Title**: *Effectiveness Assessment of Pipeline Cathodic Protection System Using Remote Sensing, Advanced Modeling, and Data Analytics*

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Section A: Business and Activities

1. Contract Activities

Contract Modifications: N/A

Educational Activities:

* + Student mentoring:

Xingsen Yang (PhD student in Civil Engineering at Rutgers); Xiao Chen (PhD student in Civil Engineering at Rutgers), Jay Shah (Postdoc at Rutgers) worked on literature review and numerical modeling of CP performance.

Asley Chow (undergraduate in Corrosion Engineering at U. of Akron) and Cecilia Segretario (undergraduate in Chemical Engineering at U. of Akron) worked on literature review and laboratory tests of CP performance.

* + Educational activities:

The PI introduced the knowledge of pipeline integrity management system in the graduate course – Infrastructure Management System taught at Rutgers University.

The Co-PI (Dr. Zhou) introduced the concept of cathodic protection in the undergraduate course - Introduction to Corrosion Science and Engineering at The University of Akron.

Dissemination of Project Outcomes: A review paper is currently being drafted for submission.

1. Financial Summary

Federal Cost Activities:

* + PI/Co-PIs/students involvement:

PIs’ summer salary and students’ tuition/stipend are partially charged.

* + Materials purchased/travel/contractual (consultants/subcontractors):

Software license is purchased for multi-physics simulation; Bulk plastic containers are purchased for GPR testing on soils.

Cost Share Activities:

* + Cost share contribution:

Cost share is provided by PIs’ academic time as budgeted in the proposal.

1. Project Schedule Update

Project Schedule: On schedule

Corrective Actions: N/A

1. Status Update of the 4th Quarter Technical Activities

**Task 2: Laboratory Tests of CP Performance under Various Factors**

To conduct laboratory tests on metal corrosion under soil environment, previous studies are reviewed and the testing conditions are summarized, including soil properties, soil composition, metal type, testing method, and CP levels.

As shown in Table 1, soil type, pH, and conductivity are summarized. A more acidic environment is more often used. The conductivity of the soil varies from 0.008 to 1.454. Table 2 shows the compositions of the soil from previous papers. The soil mainly consists of sand, silt, and clay. The percentage of each component varies in soil from different areas.

Table . Soil properties in previous corrosion studies.

|  |  |  |  |
| --- | --- | --- | --- |
| **Soil** | **pH** | **Conductivity (S/m)** | **Reference** |
| Abia State  | 5.6 | 1.426  | [1] |
| Bayelsa State | 5.65 | 1.454 |
| Delta State  | 5.71 | 1.434 |
| Rivers State  | 5.64 | 1.432  |
| Test Soil | 8.17 | 0.0426  | [2] |
| Br-100 (w/ water) | 5.7 +/- 0.1 |  | [3] |
| Br-20 (w/ Na2SO4 in water) | 5.7 +/- 0.1 | 0.04545 |
| Natural Sand Soil (South-West of France) | 7.0 +/- 0.1 | 0.02  | [4] |
| [5] |
| Artificial Soil  | 7.1 +/- 0.1 |  | [6] |
| Clay Soil (three different locations) | 4.8-5.4 | 0.008, 0.01099, 0.07752  | [7] |
| Eight Samples of Soil | 8.40-9.10 |  | [8] |
| Soil from Ankara (Turkey) | 7.92 | 0.016  | [9] |
| Soil from Southeast China | 4.0-4.5 |  | [10] |
| Yingtan Soil | 4.5 |  | [11] |

Table Soils and their compositions in previous corrosion studies.

|  |  |  |
| --- | --- | --- |
| Soil | Composition | Ref |
| **% Sand** | **%Silt** | **%Clay** | **Others** |
| Abia State | 61.5 | 23.9 | 14.6 | **-** | [1] |
| Bayelsa State | 60.1 | 29.2 | 10.7 | - |
| Delta State | 59.2 | 17.6 | 14.2 | - |
| Rivers State | 58.8 | 21.3 | 19.9 | - |
| Br-100/Br-20 | 72.9 | 17.4  | 9.7 | **-** | [3] |
| Natural Sand Soil | 88.4  | 8.1  | 3.5 | **-** | [4] |
| [5] |
| Artificial Soil | 83.0  |  | 14.5 | % Peat 2.5 | [6] |
| Clay Soil | Fe: 250-550 mg/kg, Cl: 2-31 mg/kg | [7] |
| Eight Samples of Soil  | 31.97 | 38.06 | 19 | %Gravel 4.92 | [8] |

Table 3 shows the metals used in the previous studies. Most of them use the API 5L X series steel, which is commonly used for pipelines in the field.

Table Metal used in previous corrosion studies.

|  |  |
| --- | --- |
| Metal | Reference |
| API 5L X42  | [1] |
| API 5L X52  | [12] |
| API 5L X65  | [9] |
| API 5L X70 | [4] |
| [5] |
| [8] |
| API 5L X80  | [11] |
| API 5L X100  | [13] |
| Cast iron | [2] |
| S235JR Carbon steel | [6] |

Table 4 shows the testing methods used in the previous studies for corrosion behavior of metals.

Table Testing method in previous corrosion studies.

|  |  |
| --- | --- |
| Testing method | Ref. |
| Used a KERRO BLG 2000 electronic scale | [1] |
| ASTM G-01 (mass loss) | [2] |
| NF ISO 8407: 2010 standard (weight loss) | [3] |
| [4] |
| [5] |
| ASTM G102 | [12] |

Table 5 displays the CP levels utilized in previous studies for the corrosion behavior of metals under cathodic protection. The CP potential varies from -0.55 to -1.2 V vs. CSE.

Table CP levels used in previous corrosion studies.

|  |  |  |
| --- | --- | --- |
| CP levels | Reference |  |
| -0.55 ~ -0.8; 0.7 ~ -0.75 V vs. CSE | [3] |  |
| -0.70; -1.10 V vs. CSE | [4] |  |
| -0.78 V vs. CSE | [5] |  |
| -1.0 ~ -1.2 V vs. CSE | [6] |  |
| -250 ~ +300 mV vs. OCP | [12] |  |
| -0.25, -0.45 V vs. CSE | [7] |  |
| -0.9 V, -1.1 V, -1.3 V, -1.5 V vs. SCE | [9] |  |
| 1.2V ~ 0V vs. SCE | [13] |  |
| -1.0 V, -0.85 V, -0.78 V, -0.7 V vs. CSE | [11] |  |

**Task 3: Modelling and Simulation of CP Performance**

The research team has developed a coupled electro-chemical-soil model for CP effectiveness assessment.

**Current distribution theory**

In cathodic protection systems, soil functions as an ionic conductor, enabling the passage of current, while the current density can be expressed as the sum of ion fluxes, as illustrated in Equation 1 (Nichols et al. 2008). The Nernst-Planck equation governs the flux of species *Ni* in an ideal electrolyte solution. This equation outlines the transport mechanisms of solute species through three primary processes: diffusion, migration, and convection, which are represented in the respective additive terms of Equation 2 (Nichols et al., 2008).

$i\_{l}=F\sum\_{i}^{}z\_{i}N\_{i}$ (1)

Where, *il* is the current density in the electrolyte (A/m2); *F* is the Faraday constant (C/mol); and *Ni* is the flux of species *i* (mol·m2/s) with charge number *zi.*

$N\_{i}=-D\_{i}∇c\_{i}-z\_{i}u\_{m,i}Fc\_{i}∇Φ\_{l}+c\_{i}u$ (2)

Where, *ci* is the concentration (mol/m3); *Di* is the diffusion coefficient (m2/s); *um,i* is its mobility (s mol/kg); *Φl* is the electrolyte potential (V); and *u* is the velocity vector (m/s).

However, the common approach to electrochemical theory is often overly complex for practical applications. By assuming electroneutrality, which eliminates the convection term, along with negligible concentration gradients for the ion carrying the current, thereby removing the diffusion term, and considering a nearly constant composition of charge carriers, the expression for current density in the electrolyte can be reduced. This simplification is grounded in Ohm’s law and the principle of current conservation, as demonstrated in Equations 3 and 4 (Ludwig et al., 2002).

$i\_{l}=-σ\_{l}∇Φ\_{l}$(3)

$∇i\_{l}=Q\_{l}$(4)

Where, *Ql* denotes a general current source term (A/m3);$i\_{l}$is the current density of electrolyte (A/m2); $σ\_{l}$ is the conductivity of electrolyte (S/m); and $Φ\_{l}$ is the electrolyte potential (V).

In the context of pipe corrosion, the pipe functions as the electrode, where chemical reactions take place at both the anode and cathode. To describe the electrochemical reactions occurring on the pipe, the electrode kinetics were modeled using Tafel equations, as detailed in Equations 5 through 7 (Seri and Siree 2017).

$i\_{c, local}=-i\_{o,c}×10^{\frac{η }{A\_{c}}}$ (5)

$i\_{a, local}=-i\_{o,a}×10^{\frac{η }{A\_{a}}}$ (6)

 $η=Φ\_{s}-Φ\_{l}-E\_{eq}$ (7)

Where, *ic* is the local current density at the cathode (A/m2); *ia* is the local current density at anode (A/m2); *i0* is the exchange current density (A/m2); *η* is the reaction overpotential; *Aa* and *Ac* are the Tafel slopes; $Φ\_{s}$ is electric potential; $Φ\_{l}$ is electrolyte potential (V); *Eeq* is the equilibrium potential (V).

Specifically, for cathodic reaction where oxygen serves as the reactant, its concentration and fluctuations can influence the intensity of the electrochemical reaction. To account for the effect of oxygen concentration, the corresponding Tafel expression has been modified to:

$i\_{O\_{2}}=-\frac{c\_{O\_{2}}}{c\_{O\_{2}}^{ref}}×i\_{0,O\_{2}}×10^{\frac{η\_{O\_{2}} }{A\_{c,O\_{2}}}}$ (8)

Where, *cO2* is the concentration of the diffusing oxygen at the pipe level (mol/m3), *cO2, ref* is the reference oxygen concentration (atmospheric).

Examples of the electrochemical reaction parameters mentioned in the model are presented in Table 6. (Zhang et al. 2023).

**Table 6. Electrode reaction parameters (Zhang et al. 2023)**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Unit** | **Fe** | **O2** | **H2** |
| Equilibrium potential, Eeq | V | -0.76 | 0.189 | -1.03 |
| Exchange current density, i0 | A/m2 | 7.1E-5 | 7.7E-7 | 1.1E-2 |
| Tafel slope, A | V/decade | 0.41 | -0.18 | -0.15 |

Given that anodic and cathodic reactions occur simultaneously, the reaction rate can be determined by evaluating the local current density at the anode or cathode, as illustrated in Equation 9. Subsequently, the metal corrosion rate is calculated through the application of Equation 10 (Stansbury and Buchanan 2000).

$R=\frac{-vi\_{local}}{nF}$ (9)

Where, *R* is the reaction rate (mol/(m2·s)); *ilocal* is the local current density at electrode (A/m2); *n* is the number of participating electrons; *v* is stoichiometric coefficient for reaction species (v=1 for iron, v=-1 for oxygen, and v=1 for hydrogen); *F* is the Faraday’s constant (*F*=96485 C/mol).

$C\_{rate}=\frac{MR}{ρ}$ (10)

Where, *Crate* is the corrosion rate (mm/year); *M* is the molar mass of the cathode (58g/mol for iron); *R* is the reaction rate (mol/(m2·s)); *ρ* is the density (7860kg/m3 for iron).

**Model geometry**

In this research, a three-dimensional finite element model was established using COMSOL Multiphysics to evaluate the behavior of CP system under varying environmental factors, particularly soil moisture content. The schematic of the model is shown in Figure 1. The soil electrolyte was 10m long, 10m wide and 4m deep. A 10m long pipeline with a diameter of 0.3m was buried at 2.5m depth. A 0.5m high anode with a diameter of 0.2m was also buried at 2.5m depth.



Figure 1. Model diagram

**Transport of oxygen**

As previously mentioned, oxygen acts as a key reactant in the cathodic reaction, and its concentration significantly influences both the intensity of the cathodic reaction and the effectiveness of CP. To account for the concentration changes and transport of oxygen, Fick's law was applied to describe its diffusion behavior, as shown in Equation 11 (Altmann et al. 2012).

$-D\_{i}∇c\_{i}+uc\_{i}=R$ (11)

Where, *ci* is the concentration (mol/m3); *Di* is the diffusion coefficient (m2/s); *u* is the velocity vector (m/s); and *R* is the reaction rate expression (mol/(m3·s)).

In this study, the transport of chemical species was integrated with the electrochemical reactions by constraining the reaction rate according to the species concentration, as shown in Equation 8, allowing the model to incorporate the effects of the surrounding environmental conditions. Given that the molar mass of water far exceeds that of oxygen in the soil electrolyte, the corrosion process is predominantly controlled by the concentration of oxygen.

**Material properties related to moisture content**

As one of the key properties of soil, moisture distribution affects both the flow of electric current and the transport of oxygen within the soil. Increased moisture enhances the movement of charged particles, thereby improving electrical conductivity, while the presence of water restricts oxygen diffusion to the pipe surface.

In this study, the effects of moisture content on both soil electrical conductivity and oxygen diffusion rate were analyzed. Equation 12 illustrates the specific relationship between the moisture content and the electrical conductivity of clay soil (Kibria and Hossain, 2012).

$σ\_{l}=2.73×θ^{1.64}$ (12)

Where,$σ\_{l}$is the soil electrical conductivity (mS/m*);* $θ$ is the moisture content (%).

Additionally, the correlation between the degree of water saturation and the oxygen diffusion rate is represented in Equation 13 (Azoor et al., 2019).

$D=-0.009×S^{3}+0.0026×S^{2}-0.004S+0.01$ (13)

Where, $D $is the diffusion rate (cm2/s*);* $S$ is the saturation degree, which equals to moisture content divided by the porosity.

**Moisture profile**

A 3-D hydraulic model was established to analyze moisture changes in the soil. The Richard’s Equation, which describes the change in water content over time as a function of water infiltration and other environmental variables, was used as the governing equation, as shown in Equation 14 (Farthing and Ogden, 2017). For unsaturated water flow behavior, both volumetric moisture content and hydraulic conductivity will change with the matric suction. The relationship between moisture content and matric suction was represented using the Soil Water Characteristic Curve (SWCC), and the relationship between hydraulic conductivity and matric suction was represented using the Soil Permeability Characteristic Curve (SPCC). The Van-Genuchten (V-G) equations shown in Equation 15 and 16 are employed to interpret both these curves, providing a mathematical framework for capturing the complexities of unsaturated soil behavior (Farthing and Ogden, 2017).

$ρ\frac{∂θ}{∂t}=∇(\frac{K\_{s}}{g}K\_{r}(∇p+ρg)$ (14)

Where, *ρ* is fluid density; $θ$ is the volumetric moisture content; t is the time; $K\_{s}$ is the saturated hydraulic conductivity; *g* is the acceleration of gravity; *Kr* is the relative hydraulic conductivity; *p* is the pressure.

 $θ=θ\_{r}+\frac{θ\_{s}-θ\_{r}}{(1+|αh|^{n})^{\frac{n-1}{n}}}$ (15)

$K\_{s}=K\_{r}\frac{[1-(\frac{|αh|^{n}}{(1+|αh|^{n})})^{\frac{n-1}{n}}]^{2}}{(1+|αh|^{n})^{\frac{n-1}{n}}}$ (16)

Where, $θ\_{r}$ is the residual moisture content; $θ\_{s}$ is saturated moisture content; $h$ is the matric suction; $α$ and n are fitting parameters.

**CP system implementation**

The widely used impressed current cathodic protection (ICCP) system provides flexibility in controlling the protective current by using an external voltage from a rectifier connected to an AC power source (Evitts & Kennell, 2018). This setup raises the anode to a higher potential than the pipe, causing current to flow from the anode through the soil to the pipe, thereby delivering the CP current.

In ICCP systems, the primary function of the anode is to deliver current rather than to participate in significant electrochemical reactions. Therefore, the anodes used in the ICCP systems are usually made from materials that are either inert or highly resistant to corrosion, such as mixed metal oxides (MMO), platinum-coated titanium, or silicon iron (Evitts & Kennell, 2018). These materials are chosen precisely because they undergo very little chemical reaction, even when exposed to high potentials.

In this model, the electrochemical reactions at the anode are considered negligible and an external potential is applied to the anode to establish a higher potential relative to the pipe. This drives the current from the anode to the pipe, shifting the pipe’s potential in a more negative direction. The potential applied to the anode influences both the current density and the potential on the pipe. The effectiveness of the CP system is evaluated based on the -0.85 V protection criterion and the corrosion rate observed on the pipe surface. By controlling the applied potential, it is also possible to observe and evaluate fluctuations in the CP system’s performance as environmental conditions change.

**Boundary Conditions**

At the soil surface exposed to the atmosphere, a constant concentration boundary is imposed with a concentration of *cO2,ref* equal to 8.6 mol/m3. Except for the ground level of soil, which is exposed to the air, other surfaces of the soil in the model are adjusted as an infinite boundary, which means current do not block at those surfaces.

Section B: Detailed Technical Results in the Report Period

# Background and Objectives in the 1st Annual Report Period

The work in the 1st year is mainly to 1) conduct literature review, 2) develop laboratory test plan, and 3) develop an electro-chemical-soil model for CP effectiveness assessment.

# Research Progress

***Task 1: Literature Review, Information Collection, and Refinement of Work Plan --- Completed***

The research team has completed literature review including the topics related to 1) CP system design principle, 2) factors affecting CP effectiveness (soil condition, coating, AC/DC current, etc.), and 3) CP effectiveness assessment methods (laboratory, field, numerical modeling, data-driven).

The PI had an online meeting with the industry partner (one pipeline operator) to discuss and refine the project plan. The PI attended the annual conference of Association for Materials Protection and Performance (AMPP) in March 2024 and discussed the project with the industry partner (one consulting firm) to obtain feedback on project plan.

***Task 2: Laboratory Tests of CP Performance under Various Factors --- Ongoing***

The task is to study the effectiveness of CP through electrochemical measurements in the laboratory and provide benchmark data for CP model validation. The research team has summarized soil properties and soil composition, CP conditions, and characterization methods for investigating corrosion behavior of metals in previous studies.

***Task 3: Modelling and Simulation of CP Performance --- Ongoing***

This task is to develop a coupled electro-chemical-soil model for CP effectiveness assessment and evaluate the major factors having significant influences. The research team has developed the preliminary model for CP effectiveness assessment. The corrosion model includes characterization of two phenomena. One is electrochemical reactions on the pipeline steel surface, the other is oxygen diffusion and moisture transport during the electrochemical reactions. To accurately simulate CP performance, the transport of chemical species will be coupled with electrochemical reactions, which enables the model to take the changing environment conditions into account.

# Future work

Task 2: An experimental design and testing protocols for investigating metal corrosion under different soil conditions with CP will be undertaken. The metal, soil, and testing conditions for CP will be identified and investigated.

Task 3: An electro-chemical-soil model will be refined and validated through laboratory experiments, and then used to quantify the influencing factors on CP effectiveness.

Task 4: The remote inspection methods of soil properties and corrosion will be investigated based on laboratory tests using GPR and HIS.

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