

## Development of an Integrated Soil Corrosivity Prediction Model for Underground Metallic Structures in Semi-Arid Soils of Aurangabad District, India

Prajakta S. Matade<sup>1</sup>, Rashmi D. Pathrikar<sup>2</sup>, Sunil R. Mirgane<sup>1,2\*</sup>

<sup>1</sup>Department of Chemistry, Jalna Education Society's R.G.Bagdia Arts, S.B. Lakhotia Commerce and R. Bezonji Science College, Jalna 431203

<sup>2</sup>Rajarshi Shahu Arts, Commerce and Science College, Pathri, Chhatrapati Sambhaji Nagar – 431003.

Email: [mirganesunil@gmail.com](mailto:mirganesunil@gmail.com)

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### Abstract

The corrosion behavior of mild steel was evaluated at multiple exposure durations using the weight-loss method. The results revealed substantial differences in soil characteristics and corrosion responses across sampling sites. Industrial soils exhibited higher electrical conductivity, chloride content, and dissolved salts, along with lower resistivity, resulting in increased corrosion aggressiveness. Correlation analysis identified strong associations among conductivity, resistivity, moisture content, chloride concentration, and corrosion behavior. Clay-rich soils, which retain higher moisture levels, demonstrated increased electrochemical activity and a greater tendency for corrosion. An Integrated Soil Corrosivity Index (ISCI) was developed by combining physicochemical characteristics to predict underground corrosion intensity. The resulting model showed strong agreement with experimentally measured corrosion rates and effectively classified soils into low, moderate, and high corrosion risk categories. Principal component analysis demonstrated that conductivity, influenced by salinity and moisture-retention properties, was the primary factor determining soil corrosivity. The findings suggest that integrated multivariable analysis provides more reliable predictions of subterranean corrosion behavior than assessments based on individual soil factors. The proposed ISCI model offers a practical tool for evaluating corrosion risk, selecting appropriate materials, designing subterranean infrastructure, and ensuring the long-term protection of buried metallic structures in semi-arid regions.

### INTRODUCTION

Corrosion of underground metallic structures is a serious engineering, environmental, and economic challenge. Buried metals are in constant contact with aggressive soil environments, which are conducive to electrochemical corrosion. Soil corrosion is especially prevalent in underground pipes, storage tanks, cable sheathing, grounding systems, irrigation networks, transmission towers, and reinforced foundations. The failure of such systems can result in leakage, environmental contamination, structural damage, suspension of industrial activities, and increased maintenance expenses (Fontana, 2005; Koch et al.,

2002; Revie and Uhlig, 2008).

Soil corrosion is far more complex than atmospheric corrosion, as soil is a heterogeneous medium containing minerals, moisture, dissolved salts, gases, microbes, and organic matter. Variations in oxygen availability and moisture distribution, ionic concentration, microbial activity, and soil texture lead to localized anodic and cathodic regions on buried metallic surfaces, thus initiating electrochemical corrosion events (Jones, 1996; Romanoff, 1957; Ahmad, 2006). Moisture provides an electrolyte for ionic transport and electrochemical charge transfer at the metal–soil interface (Hamilton, 1985).

Several physicochemical characteristics, such as electrical conductivity, salinity, moisture content, chloride, sulfate, pH, and soil resistivity, control soil corrosiveness. Soil resistivity is commonly current required for electrochemical corrosion processes (ASTM International, 2013; NACE International, 2013; Romanoff, 1957). The corrosion process is accelerated by increased ionic mobility within the soil matrix, driven by higher conductivity and dissolved salt content (Li et al., 2015; Zhang et al., 2019). Aggressive ions such as chlorides and sulfates are very important to underground corrosion behavior. Chloride ions are particularly detrimental because they destabilize passive oxide coatings and promote localized corrosion, including pitting and crevice corrosion, in stainless steels (Sedriks, 1996; Li et al., 2007). Sulfate ions may also contribute to microbiologically influenced corrosion in anaerobic soil conditions (Hamilton, 1985; Melchers and Jeffrey, 2008). The soil pH also influences the solubility of metals and the stability of corrosion products. Corrosion rates are often higher in acid soils due to the increased activity of hydrogen ions, but lower in neutral or slightly alkaline soils, where the formation of partially protective oxide layers may be possible under certain environmental conditions (Evans, 1960). Corrosion susceptibility is further affected by soil texture and moisture-retention behavior, which control permeability, aeration, porosity, and electrolyte continuity. Soils rich in clay have higher moisture and dissolved salts, which diminish resistivity and increase corrosion aggressiveness. Sandy soils have relatively lower electrolyte retention and a lower corrosive tendency (McNeill, 1979).

Several investigations have shown strong links between soil physicochemical parameters and underground corrosion behavior (Li et al., 2015; Zhang et al., 2016; Wang et al., 2022). Recent investigations also reveal that integrated multivariable analysis is more reliable at predicting corrosion behavior than the isolated evaluation of individual soil factors (Xu et al., 2021; Kumar and Singh, 2023; Sharma et al., 2024). The Aurangabad district of Maharashtra widely uses buried metallic structures in agricultural lands, industrial areas, irrigation systems, and underground utility networks. Industrial contamination and agricultural activities such as fertilizers, irrigation water, and pesticides can significantly alter soil chemistry and corrosion behavior. However, comprehensive investigations linking soil physicochemical properties with underground corrosion behavior in this location are scarce.

considered one of the most reliable indicators of underground corrosion, as low-resistivity soils facilitate the flow of electrical

This is the reason the present inquiry was carried out to evaluate the corrosive properties of agricultural and industrial soils in Aurangabad district using integrated physicochemical and corrosion analyses. Soil samples were tested for conductivity, salinity, moisture content, resistivity, pH, dissolved ions, and soil texture. Gravimetric analysis under controlled exposure settings was used to study corrosion behavior. The study also aims to develop links between soil parameters and corrosion severity to assess subsurface corrosion risk in semi-arid conditions.

## MATERIALS AND METHODS

### Study Area and Soil Sampling

This study utilized soil samples obtained from agricultural and industrial areas in Aurangabad district, Maharashtra, India. The region has semi-arid weather and varied environmental features, shaped by irrigation practices, agricultural activities, and industrial operations. Forty typical soil samples were obtained from agricultural lands, industrial zones, roadside areas, and irrigation locations. Samples were obtained from depths of around 15–30 cm, which correspond to the typical burial depth of subterranean metallic structures. Samples were moved to clean polyethylene containers, air-dried, crushed, sieved, and kept in airtight containers for subsequent analysis.

### Physicochemical Analysis of Soil Samples

The physicochemical examination of soils encompassed the assessment of temperature, redox potential, electrical conductivity, salinity, moisture content, organic matter, soil resistivity, pH, and dissolved ionic species by standardized analytical techniques. Electrical conductivity and salinity were measured with a digital conductivity meter, whilst moisture content was determined by oven-drying at 105 °C. The estimation of organic matter was conducted utilizing a conventional oxidation method. Soil resistivity was quantified utilizing methods similar to the Wenner four-electrode approach and articulated in ohm·cm. These parameters substantially affect electrolyte continuity, ionic mobility, and subsurface corrosion behavior.

### Corrosion Studies

The corrosion behavior of mild steel specimens was assessed in a controlled laboratory environment using the gravimetric weight-loss method.

The specimens were mechanically polished, cleaned, degreased with acetone, dried, and precisely weighed prior to exposure. Coupons were individually implanted into soil samples and exposed for 6, 12, 24, 48, and 96 hours. After exposure, the specimens were extracted, cleaned, desiccated, and reweighed. The corrosion rate was determined from the weight loss and represented in  $\text{mg dm}^{-2} \text{ day}^{-1}$ .

### Development of Integrated Soil Corrosivity Index (ISCI)

An Integrated Soil Corrosivity Index (ISCI) was formulated utilizing a combination of physicochemical factors such as conductivity, chloride concentration, sulfate concentration, moisture content, organic matter, pH, and soil resistivity to forecast the severity of subsurface corrosion. The constructed model was validated with experimentally derived corrosion rates from gravimetric corrosion analyses.

## RESULTS AND DISCUSSION

### Physicochemical Characteristics of Soil Samples

The physicochemical characteristics of soils significantly affect subterranean corrosion behavior, as soils function as natural electrolytes containing moisture, dissolved salts, minerals, gases, and organic matter. Factors include electrical conductivity, salinity, moisture content, chloride concentration, pH, and soil resistivity, which substantially influence the electrochemical corrosion mechanisms of subterranean metallic structures. The examined soil samples from agricultural and industrial areas of Aurangabad district exhibited significant variation in physical and chemical properties, attributable to disparities in irrigation practices, industrial operations,

fertilizer application, mineral composition, and environmental conditions. Industrial soils typically showed elevated conductivity, dissolved salts, and chloride levels, while agricultural soils showed somewhat higher moisture content.

Electrical conductivity and salinity measurements revealed discrepancies in dissolved ionic concentrations across sampling locations. Elevated conductivity was typically associated with elevated chloride content and reduced resistance, thereby increasing corrosion vulnerability. The moisture concentration was adequate to sustain the electrolyte continuity necessary for subterranean electrochemical corrosion processes. Soil resistivity demonstrated significant heterogeneity throughout the study area. Soils with lower resistivity were found to be more corrosive due to their ability to promote efficient corrosion current flow. Chloride and sulfate ions greatly affected soil corrosivity by disintegrating passive oxide layers and facilitating localized corrosion.

Mechanical investigation revealed that the majority of soils were classified as sandy loam, silty loam, loam, and clay loam. Clay-rich soils held more moisture and dissolved salts, leading to reduced resistivity and heightened corrosion potential, while sandy soils had relatively lower corrosive behavior due to enhanced drainage and diminished moisture retention. The analyzed soils demonstrated varying degrees of corrosiveness, ranging from mild to severe, influenced by their physicochemical properties and environmental factors. The interplay of conductivity, salinity, moisture, chloride content, texture, and resistivity dictated the subterranean corrosion behavior of the analyzed soils.

**Table 1. Summary of Major Physicochemical Parameters of Aurangabad Soils**

Parameter	Minimum	Maximum	Mean ± SD
Temperature (°C)	26.0	32.0	29.1 ± 1.8
Redox Potential (mV)	185	391	293 ± 42
EC ( $\mu\text{S cm}^{-1}$ )	231	437	338 ± 54
Salt Content ( $\text{mg L}^{-1}$ )	193	395	279 ± 48
Moisture (%)	23.50	32.40	29.3 ± 2.1
Organic Matter (%)	0.216	0.862	0.402 ± 0.14
Resistivity ( $\text{ohm}\cdot\text{cm}$ )	637	2820	1587 ± 452
pH	6.59	8.41	7.76 ± 0.36
Chloride ( $\text{mg L}^{-1}$ )	241	593	409 ± 86
Sulphate ( $\text{mg L}^{-1}$ )	45	139	89 ± 24

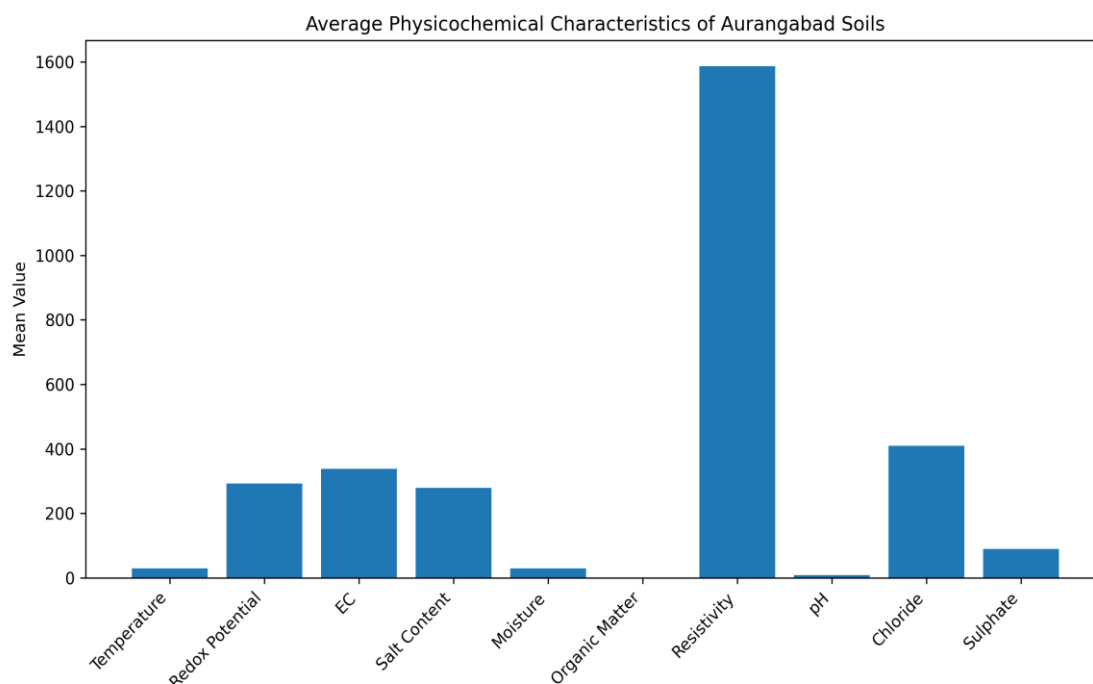


Figure 1. Average physicochemical characteristics of soil samples.

### Correlation Analysis of Major Corrosion Parameters

Correlation analysis was conducted to assess the relationships among the main physicochemical soil characteristics that influence underground corrosion behavior. Pearson correlation coefficients indicated robust relationships among electrical conductivity, moisture content, resistivity, chloride concentration, and the corrosion rate of mild steel. Electrical conductivity exhibited a robust inverse relationship with soil resistivity, indicating that elevated dissolved ionic content reduces resistance to electrical current flow and enhances

electrochemical corrosion. The concentration of chloride demonstrated a positive association with conductivity and corrosion rate, affirming the corrosive influence of chloride ions in subterranean corrosion mechanisms. Moisture content showed an inverse relationship with resistivity, as water enhances the continuity of the electrolyte and ionic mobility within the soil matrix. Clay-rich soils typically retain greater moisture, leading to reduced resistivity and heightened susceptibility to corrosion. The findings suggest that susceptibility to subsurface corrosion is predominantly governed by the interplay between salinity and moisture, rather than by any single soil characteristic.

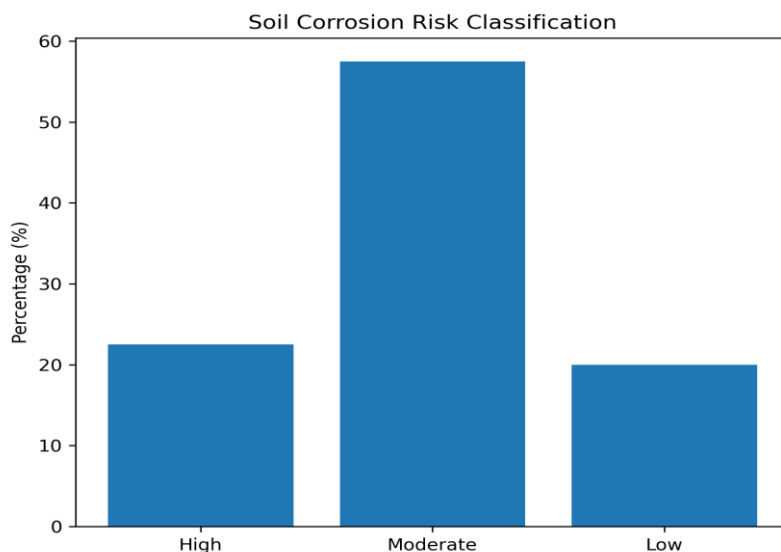
Table 2. Pearson Correlation Matrix of Major Corrosion Parameters

Parameter	EC	Moisture	Resistivity	Chloride	Corrosion Rate
EC	1.00	0.46	-0.78	0.72	0.81
Moisture	0.46	1.00	-0.65	0.41	0.63
Resistivity	-0.78	-0.65	1.00	-0.61	-0.84
Chloride	0.72	0.41	-0.61	1.00	0.76
Corrosion Rate	0.81	0.63	-0.84	0.76	1.00

The strong positive correlation between conductivity and corrosion rate, together with the strong negative correlation between resistivity and corrosion rate, confirms that low-resistivity and high-salinity soils exhibit greater underground corrosion aggressiveness toward buried metallic structures.

### Influence of Soil Resistivity on Corrosion Susceptibility

Soil resistivity is considered a highly reliable indicator of subterranean corrosion risk, as lower resistivity values indicate elevated ionic concentration, greater conductivity, and increased electrochemical aggressiveness. Soils were categorized into high (> 1300 ohm·cm), moderate (1300–2000 ohm·cm), and low (< 1300 ohm·cm) corrosion risk classes based on observed resistivity values.



**Figure 2. Distribution of soil samples under different corrosion risk categories.**

The majority of soil samples fell into the moderate-risk category, although some industrial soils showed significant corrosion severity due to increased salinity, dissolved ions, and reduced resistivity. The findings suggest that subterranean metallic

structures in the Aurangabad area require appropriate corrosion protection measures, including coatings, cathodic protection, corrosion-resistant materials, and routine monitoring.

**Table 3. Soil Corrosion Risk Classification Based on Resistivity**

Risk Category	Resistivity Range (ohm·cm)	Number of Samples	Percentage (%)
High	<1300	9	22.5
Moderate	1300–2000	23	57.5
Low	>2000	8	20.0

**Comparative Analysis of Agricultural and Industrial Soils**

A comparative study demonstrated notable differences between agricultural and industrial soils in physicochemical properties and corrosion susceptibility. Industrial soils demonstrated elevated electrical conductivity, chloride concentration, dissolved salt content, and reduced resistivity due to

industrial contamination, conductive contaminants, and anthropogenic activities.

Agricultural soils exhibited relatively greater moisture retention and salinity due to irrigation techniques and fertilizer application. Industrial soils exhibited increased electrochemical aggressiveness and elevated corrosion risk to subterranean metallic structures under the examined environmental conditions.

**Table 4. Comparative Soil Characteristics of Agricultural and Industrial Regions**

Parameter	Agricultural Soils	Industrial Soils
pH	7.82	7.63
EC ( $\mu\text{S cm}^{-1}$ )	328	392
Moisture (%)	29.8	28.9
Resistivity (ohm·cm)	1675	1284
Chloride ( $\text{mg L}^{-1}$ )	386	512
Sulphate ( $\text{mg L}^{-1}$ )	84	106

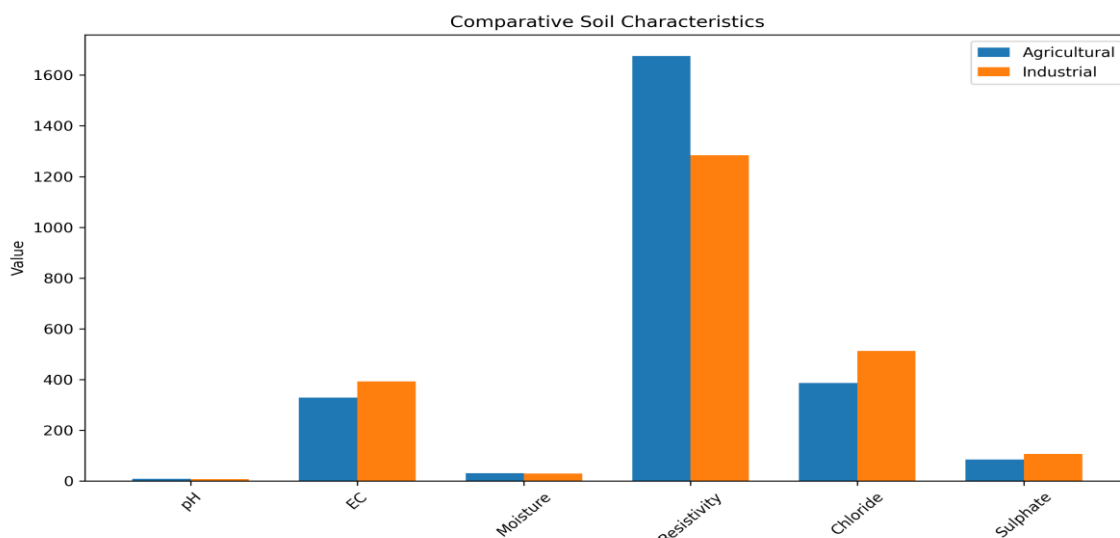


Figure 3. Comparative physicochemical properties of agricultural and industrial soils.

### Corrosion Behaviour of Mild Steel in Different Soil Environments

The corrosion behavior of mild steel was assessed under various soil conditions utilizing the gravimetric weight-loss method for exposure durations of 6, 12, 24, 48, and 96 hours. Mild steel was chosen for its widespread use in subterranean pipes, storage systems, grounding electrodes, and structural applications. The lack of a persistent passive oxide layer renders it very vulnerable to subterranean electrochemical corrosion. The findings indicated considerable heterogeneity in corrosion behavior based on soil composition, conductivity, salinity, moisture content, chloride concentration, and resistivity. The figures for weight loss increased progressively with the time of

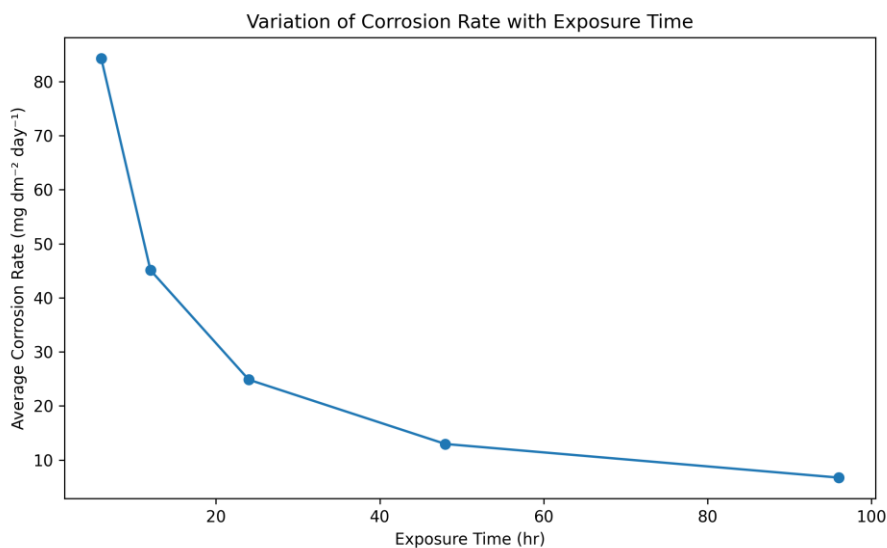
exposure due to the ongoing electrochemical breakdown of iron at the metal-soil contact. The initial corrosion rates were elevated due to direct contact between freshly exposed metallic surfaces and aggressive soil electrolytes. As exposure duration increased, corrosion products formed on the metal surface, somewhat mitigating further corrosion. Industrial soil samples demonstrated significantly higher corrosion rates due to elevated conductivity, chloride concentration, sulfate content, and lower resistivity. The most pronounced corrosion behavior was noted in soil samples affected by industrial activity, characterized by elevated dissolved ionic concentration and salinity. Sandy agricultural soils with elevated resistivity exhibited relatively less corrosion severity.

Table 5. Average Corrosion Rate of Mild Steel in Aurangabad Soils

Exposure Time (hr)	Minimum	Maximum	Average
6	73.84	110.82	84.28
12	39.64	61.48	45.12
24	20.92	34.76	24.86
48	10.92	19.86	12.96
96	5.52	10.92	6.74

The gradual decrease in corrosion rate with increasing exposure duration indicates partial stabilization of corrosion-product layers over time. However, mild steel continued to exhibit considerable corrosion activity under aggressive soil conditions, confirming its vulnerability in low-

resistivity and chloride-rich environments. Therefore, underground applications involving mild steel require suitable corrosion-protection measures such as coatings, cathodic protection systems, or corrosion-resistant materials.



**Figure 4. Decrease in average corrosion rate of mild steel with increasing exposure time.**

## CONCLUSION

This study assessed the corrosive properties of agricultural and industrial soils in Aurangabad district using comprehensive physicochemical analysis and gravimetric corrosion examinations. The findings indicated that soil characteristics, including electrical conductivity, salinity, moisture content, chloride concentration, sulfate concentration, and resistivity, substantially affect the underground corrosion behavior of buried metallic structures. Industrial soils demonstrated significantly elevated conductivity, dissolved salts, and chloride concentrations, alongside reduced resistivity, leading to increased corrosion aggressiveness compared to agricultural soils. A correlation study demonstrated robust positive associations among conductivity, chloride concentration, moisture content, and corrosion rate, while soil resistivity showed a significant negative correlation with corrosion behavior. These data affirm that susceptibility to subsurface corrosion is primarily governed by the interplay between salinity and moisture, rather than by the separate effects of specific soil characteristics.

Corrosion investigations involving mild steel revealed significant fluctuations in corrosion rate, depending on soil composition and exposure time. Industrial soils exhibited significantly higher corrosion rates due to higher ionic concentrations and lower resistivity. Despite a gradual reduction in corrosion rates with extended exposure due to partial stabilization of corrosion-product layers, mild steel continued to exhibit significant corrosion activity in aggressive soil environments.

The Integrated Soil Corrosivity Index (ISCI) effectively categorized soils into several corrosion risk classes and showed strong concordance with empirically observed corrosion behavior. The results demonstrate that integrated multivariable analysis provides a more reliable forecast of underground corrosion susceptibility than isolated soil characteristics alone. The study indicates that low-resistivity and chloride-rich soils pose a heightened corrosion risk to subsurface metallic structures in semi-arid conditions. The suggested ISCI model may serve as an effective instrument for corrosion risk assessment, material selection, subterranean infrastructure planning, and the long-term safeguarding of buried engineered systems.

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