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Research Article

Soil Property-Based Corrosion Risk Mapping of Gangapur Region Soils

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Abstract

Soil corrosion significantly contributes to the degradation of subterranean metallic structures, including pipelines, storage tanks, cable sheathing, grounding systems, and foundational materials. The corrosive properties of soil are influenced by a range of interrelated physical, chemical, and environmental factors. This study conducted a thorough physicochemical characterization of soils from the Gangapur region to assess their corrosivity. Forty soil samples from agricultural and residential areas were collected and examined using standard procedures. The examined physical parameters comprised temperature, electrical conductivity, redox potential, salinity, moisture content, organic matter, and soil resistivity. The chemical analysis encompassed the assessment of pH, total alkalinity, chloride, sulphate, nitrate, phosphate, calcium, magnesium, sodium, and potassium concentrations. A mechanical examination was conducted to determine soil texture by measuring the fractions of sand, silt, and clay. The findings revealed significant geographical variability in soil characteristics throughout the study region. The soils were primarily neutral to slightly alkaline, with pH values that reflect moderate chemical stability. Electrical conductivity and salinity indicated a modest ionic concentration in the majority of samples, although chloride concentrations at various sites suggested a possible aggressiveness towards subterranean metals. Soil resistivity measurements indicated that certain areas exhibit a moderate to high risk of corrosion. Moisture content and loamy texture were seen to promote electrolyte continuity and ion movement, thereby increasing corrosive tendencies. Through a comprehensive investigation of resistivity, salinity, moisture, and aggressive ion concentration, the soils in the Gangapur region were categorized as mildly to moderately corrosive, with some localized areas exhibiting elevated corrosion potential. Agricultural soils showed increased variability due to irrigation methods and fertilizer use, while residential soils showed evidence of human impact. The research demonstrates that physicochemical characterization is a viable method for predicting soil corrosivity and identifying suitable materials or preventive measures for subterranean installations. The produced data may function as a benchmark for corrosion management and infrastructure design in analogous semi-arid environments.

INTRODUCTION

The corrosion of metallic materials in soil environments is a significant engineering and economic challenge for underground pipes, storage tanks, cable networks, transmission towers, grounding systems, and reinforced foundations. Soil corrosion is markedly intricate, in contrast to atmospheric or aqueous corrosion, due to the heterogeneous nature of soil, which consists of mineral particles, moisture, dissolved salts, gases, microbes, and organic matter.

The interaction between subterranean metals and adjacent soil forms electrochemical cells that result in progressive material degradation, diminished service life, safety risks, leakage issues, and increased maintenance expenses (Revie and Uhlig, 2008; Fontana, 2005).

Corrosion is globally acknowledged as a primary factor in infrastructure deterioration. Research indicates that corrosion-related losses constitute a substantial percentage of the gross domestic product in numerous nations. Underground corrosion is particularly challenging to identify, as the affected structures remain concealed for extended periods before observable failure. Consequently, understanding the corrosive properties of soil is crucial for designing resilient infrastructure and selecting appropriate corrosion mitigation measures, including coatings, cathodic protection, inhibitors, and corrosion-resistant alloys (Koch et al., 2002; Romanoff, 1957).

The process of soil corrosion is fundamentally electrochemical. When a metal is embedded in soil, anodic and cathodic regions form on its surface due to variations in oxygen concentration, moisture distribution, ionic concentration, microbial activity, and metallurgical heterogeneity. At anodic areas, metal atoms undergo oxidation by losing electrons and dissolving into ionic form, while reduction events transpire at cathodic regions. In aerated soils, oxygen reduction is the primary cathodic reaction, whereas in poorly aerated or waterlogged soils, hydrogen evolution or microbial reduction may occur (Jones, 1996). The overall corrosion rate is significantly influenced by the soil's conductivity and chemical composition.

Moisture content is a critical factor influencing soil corrosivity, as it dictates the continuation of the electrolyte phase. Dry soils often exhibit lower corrosion rates due to limited ionic mobility, whereas moist soils enhance charge transport and accelerate electrochemical processes. Excessively saturated soils may become oxygen-deficient, leading to anaerobic conditions and microbiologically influenced corrosion (MIC) (Hamilton, 1985). Consequently, moisture exerts both direct and indirect influences on the deterioration of buried metal.

Soil resistivity is well recognized as an effective metric for assessing corrosive potential. Low resistivity signifies elevated ionic concentration and enhanced electrical conductivity, typically associated with increased corrosion risk. High-resistivity soils are somewhat less aggressive because they impede the current flow required for corrosion reactions. Consequently, soil resistivity investigations are frequently employed in pipeline engineering and grounding design (ASTM, 2013; Baeckmann and Schwenk, 1997). Nonetheless, resistivity alone is insufficient to comprehensively characterize corrosivity; it must be analyzed in conjunction with moisture, salinity, pH, and other chemical factors.

The chemical makeup of soil significantly influences corrosion behavior. Chloride ions are very corrosive as they compromise passive oxide coatings and facilitate localized corrosion, including pitting and crevice attack, particularly in stainless steels. Sulphate ions can engage in chemical reactions and facilitate sulfate-reducing bacteria, which produce hydrogen sulphide and expedite microbiologically influenced corrosion. Nitrate and phosphate ions affect microbial proliferation and redox chemistry, whereas soluble cations, including calcium, magnesium, sodium, and potassium, increase the ionic strength and conductivity of the soil solution (Sedriks, 1996; Uhlig, 1948).

Soil pH affects metal dissolution and the stability of corrosion products. Acidic soils typically accelerate corrosion by increasing metal solubility and facilitating hydrogen evolution. Neutral to mildly alkaline soils may promote the development of protective oxide or hydroxide layers on specific metals. Nonetheless, alkaline soils can exhibit corrosive properties when exposed to aggressive ions and sufficient moisture. Consequently, pH should be regarded as one parameter within a comprehensive corrosivity framework rather than a standalone signal (Evans, 1960).

The physical structure and texture of soil substantially influence water retention, aeration, permeability, and the diffusion of corrosive substances. Clay-rich soils retain moisture and exhibit reduced oxygen permeability, fostering conditions conducive to anaerobic corrosion processes. Sandy soils exhibit rapid drainage and are typically less corrosive owing to enhanced aeration and reduced moisture retention. Loamy soils, with balanced ratios of sand, silt, and clay, can exhibit intermediate behavior depending on salinity and moisture conditions (McNeill, 1979).

Numerous scholars have examined the correlation between soil characteristics and the corrosion of subterranean metals throughout various climatic regions. Romanoff indicated that the severity of corrosion is closely linked to soil resistivity, drainage, and salt content (Romanoff, 1957). NACE guidelines underscore the importance of soil chemistry and electrochemical assessments in the management of external corrosion of subterranean structures (NACE International, 2013). Recent studies demonstrate that integrated physicochemical analysis yields superior predictions of corrosion risk compared to any individual parameter alone (Li et al., 2015; Zhang et al., 2016).

The Gangapur region of Maharashtra, India, comprises agricultural lands and residential areas where buried pipelines, irrigation systems, electrical earthing materials, and building foundations are subjected to natural soil conditions. Agricultural practices, including irrigation, fertilizer application, and pesticide usage, can modify soil salinity, nutrient composition, and moisture levels. Residential areas may be affected by construction debris, wastewater infiltration, and human-induced pollution. Notwithstanding the practical significance of these elements, systematic data on the soil corrosivity of this region is still scarce.

This study was conducted to evaluate the corrosive properties of soils from various places in the Gangapur region using comprehensive physicochemical analysis. Forty soil samples from agricultural and residential areas were examined for temperature, electrical conductivity, redox potential, salinity, moisture content, organic matter, resistivity, pH, alkalinity, chloride, sulphate, nitrate, phosphate, major soluble cations, and texture. The aim was to ascertain geographic variability in soil characteristics, categorize corrosion risk levels, and produce foundational data beneficial for underground infrastructure planning and corrosion control in analogous semi-arid areas.

MATERIALS AND METHODS

The current study utilized soil samples obtained from the Gangapur district of Maharashtra, India, encompassing both agricultural and residential settings. The region exhibits semi-arid climatic conditions and features soils affected by irrigation, fertilizer use, agricultural operations, home waste disposal, and urbanization. The diverse land-use situations were deemed appropriate for assessing variations in soil physicochemical parameters and their impact on corrosive behavior.

Forty soil samples were obtained from various sites around the research region. The majority of the samples were sourced from agricultural areas, whereas specific samples were collected from residential areas for comparative analysis. The sampling locations comprised villages and areas, including Gangapur, Gajgaon, Mahamadpur, Shiregaon, Devali, Solegaon, Dhoregaon, Narayanpur, Padanpur, Bhoygaon, Kankori, Sultanpur, Rajangaon, Turkabad, Shirodi, and Patoda. Soil samples were obtained from a depth of around 15–30 cm, which aligns with the typical burial depth of subterranean metallic structures, including pipelines, cable sheathing, grounding electrodes, and foundation supports. Before sampling, surface vegetation, stones, and loose debris were eliminated to reduce contamination. The gathered samples were placed in sanitized polyethylene bags, appropriately marked, and conveyed to the laboratory for examination.

The samples were air-dried at ambient temperature in the laboratory to remove excess natural moisture while preserving their chemical properties. The desiccated soils were meticulously pulverized with a mortar and pestle and subsequently sieved through a standard mesh to get a consistent particle size. Homogenized samples were preserved in sealed containers until subsequent utilization. Meticulous sample preparation guaranteed uniformity and repeatability in analytical tests (Jackson, 1973; Black, 1965).

The physical characterization of the soil samples included assessments of temperature, electrical conductivity, redox potential, salinity, moisture content, organic matter, and soil resistivity. Soil temperature was measured at the sampling location with a calibrated thermometer. Electrical conductivity (EC) was quantified utilizing a digital conductivity meter in soil-water extract and reported in µS/cm. This parameter estimates the concentration of dissolved ionic species and the salinity level in the soil solution. The redox potential (Eh) was assessed with a platinum electrode in conjunction with a reference electrode and expressed in millivolts (mV), signifying the oxidizing or reducing conditions of the soil environment (APHA, 2005).

The salt concentration was derived from conductivity measurements and reported in mg/L. The moisture content was assessed using the conventional oven-drying technique. A specified mass of damp soil was desiccated at 105°C until a stable weight was attained, and the percentage moisture was determined from the mass loss. The organic matter content was assessed via a standardized oxidation method. Soil resistivity, a critical indicator of corrosivity, was assessed using methodologies analogous to the Wenner four-electrode technique and reported in Ω·cm. Reduced resistivity values signify enhanced electrical conductivity and an increased risk of corrosion (ASTM, 2013; Romanoff, 1957).

The chemical examination of the soil samples included the assessment of pH, total alkalinity, chloride, sulphate, nitrate, phosphate, calcium, magnesium, sodium, and potassium. The soil pH was determined in a soil-water suspension using a digital pH meter. Total alkalinity was assessed using acid-base titration with a standard hydrochloric acid solution. Chloride ions were quantified by argentometric titration employing silver nitrate and potassium chromate as an indicator. Sulphate concentration was assessed using the turbidimetric method, whilst nitrate and phosphate were evaluated by spectrophotometric and colorimetric processes. The concentrations of calcium and magnesium were assessed by EDTA complexometric titration, whereas sodium and potassium levels were quantified using flame photometry (Vogel, 1989; Tandon, 2005; Piper, 1966).

A mechanical study of soil samples was conducted to determine the relative proportions of sand, silt, and clay using the sedimentation method. Soils were divided into conventional textural classes based on the measured proportions. Soil texture is a critical factor affecting porosity, aeration, moisture retention, permeability, and ionic mobility, all of which influence the corrosion behavior of buried metals (NACE International, 2013).

The corrosive properties of the analyzed soils were assessed using a comprehensive interpretation of physicochemical characteristics. Significant attention was directed towards soil resistivity, electrical conductivity, moisture content, salinity, chloride concentration, sulphate content, pH, redox potential, and texture. Soils with low resistivity, high moisture content, enhanced conductivity, and substantial levels of aggressive ions were deemed to have a greater corrosive potential. A comparative investigation of agricultural and residential soils was conducted to assess the impact of land-use patterns on corrosion risk.

All investigations were conducted according to standard laboratory protocols, and the resulting data were aggregated to identify regional variation in soil parameters within the Gangapur region. The outcomes of this methodology provide a scientific foundation for assessing soil corrosivity and proposing appropriate protective measures for subterranean metallic constructions

RESULTS AND DISCUSSION

Statistical Analysis of Soil Properties

The descriptive statistical parameters of the analyzed soil samples are displayed in Table 1. The data indicated significant variability among sampling locations, demonstrating the cumulative effects of agricultural inputs, irrigation methods, natural mineral composition, and regional environmental factors. The soil pH varied from 7.38 to 8.06, with a mean of 7.74 ± 0.18, signifying neutral to slightly alkaline soils. Such pH values often promote the passivation of steel surfaces, but chloride-laden soils may still provoke localized corrosion. Electrical conductivity ranged from 274 to 494 µS/cm, with a mean of 389 ± 63 µS/cm, indicating a moderate quantity of soluble salts. The moisture content varied from 26.39% to 34.05%, with a mean of 29.90 ± 2.12%, indicating a significant water-retention capacity of the primarily loamy soils. Soil resistivity ranged from 1173 to 1755 Ω·cm, with a mean of 1486 ± 165 Ω·cm, suggesting a mild to moderate corrosive potential. The coefficient of variation (CV) indicated highest variability for sulphate and conductivity, suggesting localized salinity fluctuations across the study region.

Table 1. Descriptive statistics of selected soil parameters (n = 40)

Parameter	Min	Max	Mean ± SD	CV (%)
pH	7.38	8.06	7.74 ± 0.18	2.3
EC (µS/cm)	274	494	389 ± 63	16.2
Moisture (%)	26.39	34.05	29.90 ± 2.12	7.1
Resistivity (Ω·cm)	1173	1755	1486 ± 165	11.1
Chloride (mg/L)	349	569	463 ± 57	12.3
Sulphate (mg/L)	55	118	88 ± 16	18.2
Redox (mV)	204	396	285 ± 46	16.1

Correlation Analysis of Major Corrosion Indicators

Pearson correlation analysis was used to ascertain the interconnectedness among principal soil characteristics (Table 2). Electrical conductivity exhibited a significant inverse link with soil resistivity (r = −0.74), indicating that elevated ionic concentration reduces resistivity and increases corrosion risk.

The moisture content exhibited a negative association with resistivity (r = −0.61), suggesting that more saturated soils facilitate enhanced ionic transport. The content of chloride exhibited a positive correlation with electrical conductivity (r = 0.68) and a negative correlation with resistivity (r = −0.57), indicating its substantial impact on soil aggressiveness. These findings confirm that corrosion risk in the investigated soils is governed primarily by salinity–moisture interactions rather than pH alone.

Table 2. Pearson correlation matrix of key parameters

Parameter	EC	Moisture	Resistivity	Chloride
EC	1.00	0.42	-0.74	0.68
Moisture	0.42	1.00	-0.61	0.36
Resistivity	-0.74	-0.61	1.00	-0.57
Chloride	0.68	0.36	-0.57	1.00

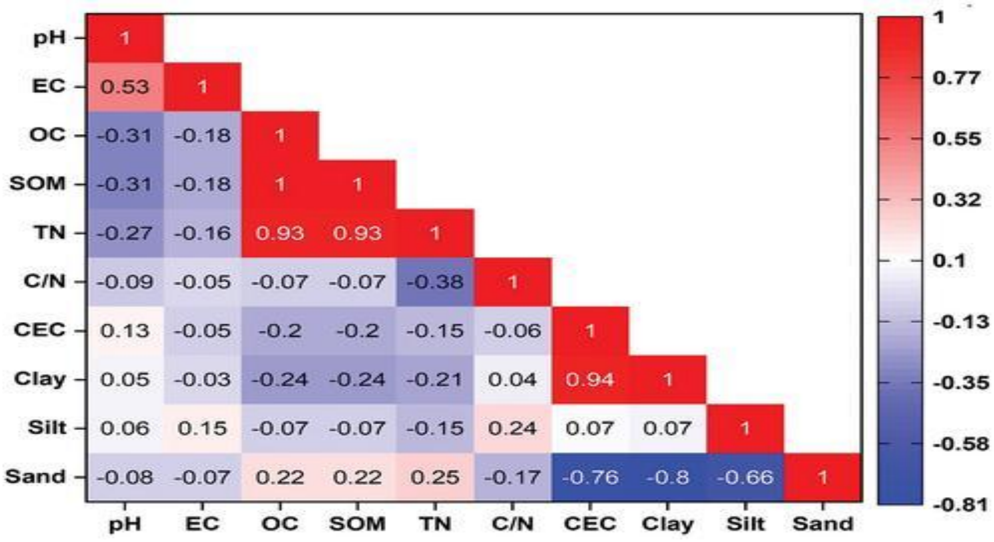

Figure 1. Correlation heatmap of soil parameters

Influence of Soil Resistivity on Corrosion Susceptibility

Soil resistivity is widely accepted as one of the most reliable screening tools for underground corrosion assessment. Based on measured values, soils were classified into three categories:

- High Risk: <1300 Ω·cm
- Moderate Risk: 1300–1600 Ω·cm
- Low Risk: >1600 Ω·cm

Accordingly, 12.5% of samples fell in the high-risk zone, 67.5% in moderate-risk zone, and 20.0% in low-risk zone. The predominance of moderate-risk soils indicates that protective coatings and periodic monitoring are advisable for buried steel infrastructure.

Table 3. Soil corrosion risk classification based on resistivity

Risk Category	Resistivity Range (Ω·cm)	No. of Samples	Percentage
High	<1300	5	12.5
Moderate	1300–1600	27	67.5
Low	>1600	8	20.0

Principal Component Interpretation

Principal component analysis was utilized to ascertain the primary factors influencing soil corrosivity in the analyzed samples. The multivariate dataset showed that two principal components accounted for most of the observed variation in soil parameters. The initial principal component (PC1) showed robust correlations with electrical conductivity, chloride, sulfate, and sodium, indicating a salinity-driven factor. Elevated positive loadings of these variables signify that dissolved salts are the principal contributors to ionic strength and electrical conductivity in the soil environment. Given that elevated salinity reduces soil resistivity and facilitates the flow of electrical current, PC1 is identified as the primary determinant of corrosion susceptibility in the research area.

The second principal component (PC2) was predominantly affected by moisture content, clay percentage, and soil resistivity, with resistivity exhibiting a negative loading. This component represents a moisture-texture factor, indicating that soils with elevated clay content and enhanced moisture retention typically exhibit lower resistivity values. Soils rich in clay and moisture typically provide uninterrupted electrolyte pathways and limited drainage, thereby promoting ongoing corrosion. The inverse relationship between resistivity and this component indicates that heightened moisture and finer texture augment conductivity and susceptibility to corrosion.

The principal component analysis indicates that corrosion behavior in the Gangapur region is predominantly influenced by soluble salt content and secondarily by soil water-retention properties. These findings underscore the need to account for both salinity-related chemical variables and physical moisture and texture characteristics to accurately estimate subsurface corrosion risk.

Agricultural vs Residential Soil Comparison

Agricultural soils exhibited significantly higher mean EC (401 µS/cm) and chloride (472 mg/L) than residential soils (366 µS/cm and 441 mg/L, respectively). This may be attributed to fertilizer use, irrigation return flow, and seasonal salt accumulation.

Table 4. Comparison of land-use categories

Parameter	Agricultural Soils	Residential Soils
pH	7.73	7.82
EC (µS/cm)	401	366
Moisture (%)	30.1	29.2
Resistivity (Ω·cm)	1468	1542
Chloride (mg/L)	472	441

These findings suggest that agricultural lands present more aggressive environments for buried utilities such as irrigation pipelines and earthing rods.

Integrated Corrosion Risk Model

A composite corrosion index was developed using normalized EC, chloride, moisture, and inverse resistivity values. Based on the index, localized high-risk zones were identified in samples S1, S4, S6, S30, and S35.

Table 5. Highest corrosion-prone sampling sites

Sample	EC	Chloride	Resistivity	Risk Rank
S1	437	569	1190	1
S4	396	460	1173	2
S30	474	563	1390	3
S6	491	479	1427	4
S35	277	563	1571	5

Comparison with Previous Studies

The observed inverse relationship between conductivity and resistivity agrees with Romanoff's underground corrosion model and later NACE standards. Similar moderate corrosion susceptibility in cultivated semi-arid soils has been reported in western India and Middle Eastern agricultural environments, where irrigation-induced salinity governs buried steel deterioration.

CONCLUSION

The study found that soils in the Gangapur region exhibit mild to moderate corrosivity, with certain localized areas presenting a higher risk of corrosion. Variations in electrical conductivity, moisture content, chloride concentration, and soil resistivity were identified as the primary factors influencing soil corrosivity. Agricultural soils were more aggressive than residential soils, primarily due to fertilizer application and irrigation. Salinity and moisture emerged as the dominant factors controlling underground metal corrosion. These findings provide essential baseline data for selecting appropriate materials, corrosion protection strategies, and maintenance plans for buried structures in the region.

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