

CORROSION-INDUCED DEGRADATION OF BURIED FOUNDATIONS IN ROMANIAN 400 kV GUYED TOWERS

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Buried foundations have a critical role in maintaining the structural integrity of high-voltage overhead transmission lines. In the case of 400 kV guyed towers operating in Romania, long-term exposure to aggressive soil environments could lead to progressive degradation mechanisms that are often difficult to detect during routine inspections. The potential of degradation can significantly increase the risk of structural failure. The present work examines corrosion-related processes affecting buried steel and reinforced concrete foundations and discusses their part to the gradual reduction in structural reliability of the transmission towers. Particular attention is given to environmental conditions specific to transmission corridors, such as soil moisture variability, chloride contamination, oxygen availability, and electrical resistivity. Unlike conventional corrosion analyses, the present work interprets degradation mechanisms from a power system reliability perspective, highlighting their almost certain impact on tower stability and collapse risk. Based on electrochemical models and engineering practice consideration, The study also evaluates commonly applied protection and rehabilitation techniques, including coatings, cathodic protection, corrosion inhibitors, and durability-enhancing concrete solutions. It can be reasonably assumed that effective risk mitigation in high-voltage systems requires not only appropriate design solutions, but also continuous monitoring and timely intervention strategies adapted to site-specific conditions. The findings support the development of integrated asset management approaches aimed at reducing failure probability and extending the service life of transmission infrastructure.

Keywords guyed tower degradation, overhead transmission lines, steel structures, buried foundations, cathodic protection, durability, service life prediction

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1. Introduction

In practical field conditions, the reliability of high-voltage overhead transmission lines depends not only on conductor performance but also on the structural integrity of tower foundations. In Romania, 400 kV guyed towers are frequently installed in diverse soil conditions, where long-term environmental

exposure may lead to progressive and always underestimated degradation mechanisms [3][4][7].

In practice, field observations indicate that failures of transmission structures are rarely caused by a single factor; instead they result from the cumulative effect of mechanical loading, environmental exposure, and material degradation processes, among which corrosion plays a major role [1][2][15]. In particular, buried steel and reinforced concrete foundations are highly vulnerable due to limited accessibility and the difficulty of direct inspection in operational conditions [18][19].

This study contributes by establishing a direct connection between corrosion-induced degradation mechanisms and the increasing risk of instability, integrity, in high-voltage guyed towers, with specific reference to Romanian 400 kV transmission lines [23][24].

From an operational standpoint, in Romanian transmission corridors, understanding the link between subsurface degradation and structural instability is essential for preventing unexpected failures and improving maintenance planning [20][26].

This paper focuses on the corrosion-related mechanisms that may contribute, directly or indirectly, to increasing the risk of tower collapse. Also contributes by linking corrosion-induced degradation mechanisms directly to structural risk in high-voltage guyed towers, based on conditions specific to Romanian 400 kV transmission lines [11][26][27].

Unlike conventional corrosion studies, the present work interprets degradation from an operational risk perspective relevant to power system reliability [5][8][28].

2. Materials and Methods

2.1 Degradation mechanisms in soil

A. Environmental factors.

Corrosion of buried steel structures is primarily an electrochemical process governed by soil composition and environmental conditions, where soil moisture acts as an electrolyte, facilitating ionic transport and accelerating corrosion reactions. Highly saturated soils typically exhibit low electrical resistivity, which significantly increases corrosion rates [12][20].

Soil chemistry has a key role in material degradation. Chlorides disrupt protective oxide layers, promoting anodic dissolution. While sulfates enhance microbiological activity. Acidic environments, generally, accelerate corrosion processes, whereas alkaline conditions may provide partial protection through passive film formation.

Oxygen availability directly affects cathodic reactions. Differential aeration conditions lead to localized electrochemical cells, particularly in heterogeneous soils. In anaerobic environments sulfate-reducing bacteria can induce microbiologically influenced corrosion (MIC) further intensifying degradation.

B. Degradation of Buried Steel Structures.

Buried steel foundations are affected by several corrosion mechanisms, including galvanic corrosion, stray current corrosion, and localized attack [26]. Galvanic corrosion occurs when dissimilar metals (such as galvanized steel and copper grounding systems) are electrically connected in the presence of an electrolyte. In this configuration steel acts as the anode and corrodes preferentially [16].

Stray current corrosion is caused by external direct-current sources (such as HVDC systems or protected pipelines) leading to accelerated material loss.

Heterogeneous soil conditions generate localized anodic and cathodic regions resulting in severe localized corrosion, as illustrated in Figure 1.

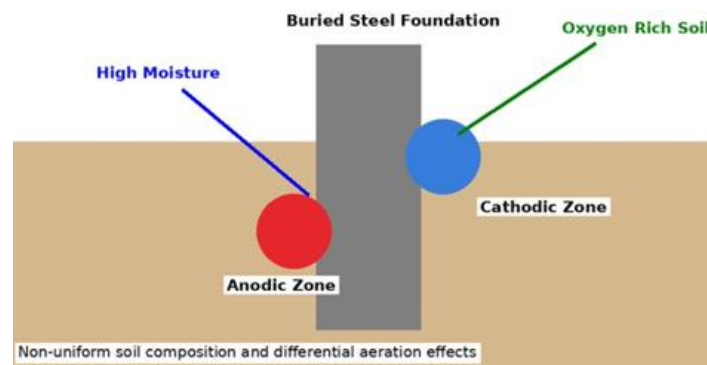


Figure 1. Conceptual depiction of underground degradation caused by non-uniform soil characteristics, oxygen availability, and variable moisture surrounding buried steel foundations.

C. Degradation of Reinforced Concrete Foundations.

In reinforced concrete structures, corrosion is primarily triggered by chloride ingress and carbonation.

Chlorides penetrate concrete pores and disrupt the passive layer protecting steel reinforcement. Meanwhile carbonation reduces alkalinity, leading to depassivation.

Once corrosion initiates, the expansion of corrosion generate internal stresses, causing cracking, delamination and eventual spalling of concrete cover, significantly reducing structural durability.

In realistic field conditions, such non-uniform degradation processes are often difficult to detect and may remain unnoticed until significant structural damage has already occurred [3][4][21].

3. Results and Discussion

3.1 Service Life Prediction

Predicting service life is highly complex due to the interaction of multiple environmental factors.

The corrosion current density is defined by:

$$i_{\text{corr}} = B / R_p \quad (1)$$

Chloride transport is modeled using Fick's second law:

$$C(x,t) = C_s [1 - \text{erf}(x / (2\sqrt{D_{\text{cl}} t}))] \quad (2)$$

Corrosion initiation occurs when:

$$C(c, t_i) = C_{\text{cr}} \quad (3)$$

The initiation time is:

$$t_i = c^2 / \{4D_{\text{cl}} [\text{erf}^{-1}(1 - C_{\text{cr}} / C_s)]^2\} \quad (4)$$

Carbonation depth follows:

$$x_c = k_c - \sqrt{t} \quad (5)$$

Corrosion begins when:

$$x_c = c \quad (6)$$

Propagation phase:

$$p(t) = 0.0116 * i_{\text{corr}} * t_p \quad (7)$$

$$d(t) = d_0 - 2p(t) \quad (8)$$

Total service life:

$$t_{\text{SL}} = t_i + t_p \quad (9)$$

The parameters incorporated into the governing equations correspond to well-established quantities widely recognised in corrosion engineering and science.

The deterioration process is divided into:

- Initiation phase
- Propagation phase

(as shown in **Figure 2**).

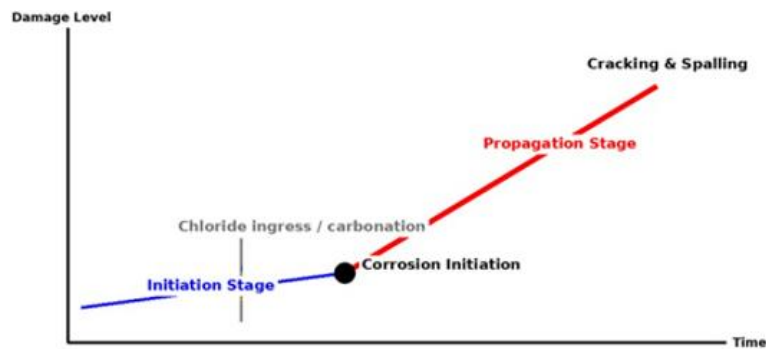


Figure 2. Deterioration for reinforced concrete structures subjected to corrosion, showing the initial stage and the propagation stage of degradation.

From an operational perspective, accurately estimating the transition between corrosion initiation and propagation remains an upper key challenge in maintenance planning [6][8].

3.2 Corrosion Protection Techniques

The vulnerability of buried steel foundations arises from a paradox inherent to underground infrastructure: the most consequential degradation processes evolve within an environment that remains largely inaccessible to routine inspection. Within this concealed domain, corrosion acts as a slow yet persistent source of uncertainty, progressively modifying both the geometry of structural components and the distribution of stresses transmitted through the foundation system. The resulting deterioration is seldom uniform, frequently emerging as highly localised damage governed by small-scale variations in soil chemistry, moisture conditions, and electrochemical potential.

From this perspective, corrosion protection should be regarded as a means of controlling the evolution of a complex soil–structure interaction process rather than merely limiting material loss. Its objective extends beyond preserving steel section, encompassing the retention of mechanical capacity, structural robustness, and operational reliability throughout prolonged periods of exposure. This distinction becomes particularly significant for extra-high-voltage transmission infrastructure, where foundation performance is directly linked to network security, system resilience, and the continuity of power transmission.

The protection methods discussed in this chapter are therefore evaluated according to their ability to modify the conditions that sustain corrosion activity, disrupt degradation pathways, and reduce the likelihood of performance deterioration throughout the service life of the structure. In this regard, effective corrosion control should be viewed not simply as a preventative measure, but as a fundamental component of infrastructure stewardship, aimed at preserving the long-term functionality of foundation systems subjected to complex and evolving geotechnical environments.

A. Metallic and Non – Metallic Coatings.

Hot-dip galvanization provides sacrificial protection, while thermal spraying enhances performance in severe environments. Should consider that duplex systems (galvanization + epoxy) significantly increase durability [7].

Epoxy coatings act as barriers, but are sensitive to mechanical damage, which may initiate, unknowingly, localized corrosion.

B. Concrete Quality and Waterproofing.

Low-permeability concrete reduces chloride diffusion and water ingress. Supplementary, cementitious materials improve pore structure and durability.

Waterproofing systems (membranes + multilayer sealing) offer superior moisture protection [16].

C. Corrosion Inhibitors.

Chemical inhibitors would reduce corrosion rates without altering concrete properties. Calcium nitrite is widely used, while organic inhibitors form protective films on reinforcement.

They can be applied preventively, but also during rehabilitation.

D. Advanced Reinforcement Materials.

Epoxy-coated reinforcement and stainless-steel rebars significantly improve durability in aggressive environments. Duplex and austenitic steels are particularly effective against chloride-induced corrosion.

E. Cathodic Protection.

Cathodic protection prevents anodic dissolution by converting steel into a cathode.

Types:

- sacrificial anodes
- impressed current systems

This method is highly effective but requires monitoring and maintenance.

Operational principles are illustrated in **Figure 3**.

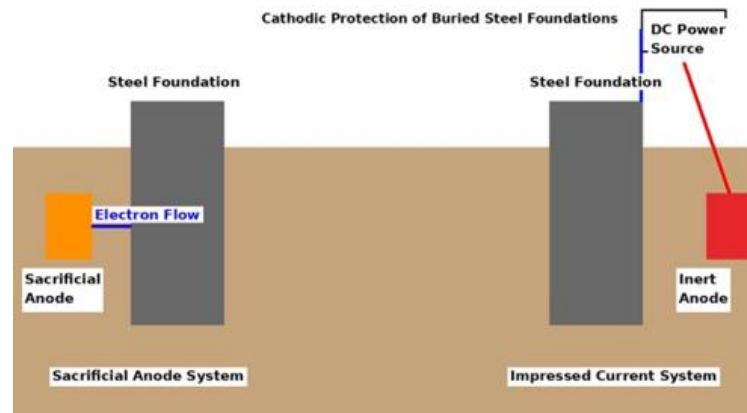


Figure 3 Cathodic protection systems applied to buried steel foundations: sacrificial anode systems and impressed current systems

In practice, the effectiveness of these protection systems largely depends on proper installation and long-term monitoring, especially along extended transmission corridors [15][18][24].

3.3 Rehabilitation of Existing Foundations

Foundation rehabilitation emerges at the point where deterioration can no longer be regarded as a purely material phenomenon and begins to influence structural performance. For buried steel foundations affected by corrosion, the challenge extends beyond the replacement of lost material or the repair of isolated defects. It involves the restoration of confidence in a structural system whose condition has been progressively shaped by decades of interaction between engineered components and the surrounding ground environment.

In contrast to new design, rehabilitation is undertaken in the presence of uncertainty. Decisions must be informed by imperfect knowledge of the extent of degradation, the variability of in-service conditions, and the future demands that will be imposed upon the structure. As a consequence, successful rehabilitation requires a balance between structural strengthening, durability enhancement, and practical constructability, whilst maintaining the continuity of network operation.

The methods discussed in this chapter are considered in terms of their capacity to recover structural resilience, limit the progression of damage, and preserve the functional role of existing foundations over extended periods of service. Rather than representing a response to past deterioration alone, rehabilitation may be viewed as a means of influencing the future trajectory of foundation performance and, ultimately, the long-term dependability of the transmission network.

Degraded foundations require rehabilitation to restore structural performance.

- A. Common techniques:
 - localized repair and coatings
 - realkalization
 - electrochemical chloride extraction
 - migrating corrosion inhibitors
- B. For steel foundations:
 - excavation
 - cleaning
 - replacement of corroded components
 - protective coatings
 - concrete encapsulation

Non-destructive methods (e.g., guided wave testing) enable early detection of internal damage [23][29].

3.4 Integrated Corrosion Management Framework

An integrated corrosion management framework recognises that the long-term performance of buried foundations is governed not by individual mitigation measures, but by the interaction between assessment, monitoring, protection, and rehabilitation strategies. By combining these elements within a coherent engineering methodology, it becomes possible to reduce uncertainty, anticipate deterioration trends, and sustain the reliability of transmission infrastructure throughout its operational lifespan.

Modern asset management integrates:

- prevention
- monitoring
- rehabilitation

Figures 4 and 5 show the:

- interaction between degradation and protection
- correlation between corrosion rate and damage evolution

Efficient strategies require adaptation to:

- soil aggressiveness
- operational lifespan
- infrastructure criticality

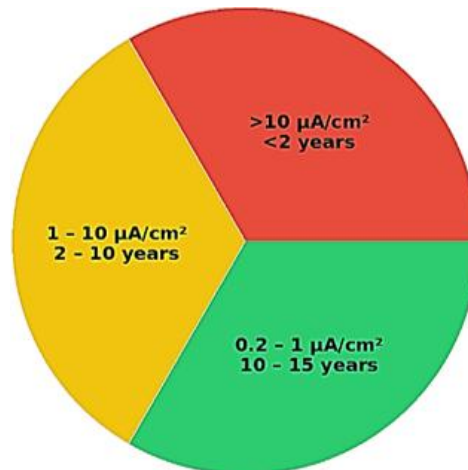


Figure 4. Degradation in buried steel foundation. **Figure 5.** Circular illustration of corrosion rate and estimated corrosion development.

This paper presents a technical and economical evaluation regarding the implementation of energy infrastructure protection systems and backup electrical solutions. The analysis focuses on investment profitability, sustainability, and operational reliability. Reliable power supply is essential for ensuring operational continuity within critical infrastructures and modern life. Unexpected interruptions may generate financial losses, technical failures, and operational instability. [21,29] The proposed investment aims to improve infrastructure reliability through the implementation of advanced protection systems. [2][9][10] The economic feasibility of the proposed project is evaluated using financial indicators such as Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period.

$$NPV = \sum [(R_i - C_i) / ((1+d)^i)] - I^0 \quad (10)$$

where R_i represents annual revenues, C_i denotes operating costs, d is the discount factor, and I^0 represents the initial investment.

$$NPV = \sum [(R_i - C_i) / ((1+d)^i)] - I^0 \quad (11)$$

The Internal Rate of Return corresponds to the discount rate for which the Net Present Value becomes zero.

$$NPV = \sum [(R_i - C_i) / ((1+d)^i)] - I^0 \quad (12)$$

The payback period indicates the number of years necessary to recover the initial investment through annual savings. The proposed investment includes protection systems for high-voltage electrical infrastructure and backup generators designed to ensure continuous power supply during emergency situations [11][14][17]. Economic simulations indicate that the project may brake even its investment within approximately 8 to 10 years, depending on operational conditions and financial assumptions (Table 1).

Table 1. Economic calculation

Year	Financial Savings	Revenues	Installation Cost (IC) + Equipment	Total Expenses	Net Cash Flow (NCF)	IRR (Internal Rate of Return)	NPV (Net Present Value)	Payback Period (PP)
1	12,000.00	12,000.00	100,000.00	100,000.00	-88,000.00		10,909.09	4.65
2	12,180.00	12,180.00		0.00	-75,820.00		20,975.21	
3	12,362.70	12,362.70		0.00	-63,457.30		30,263.49	
4	12,548.14	12,548.14		0.00	-50,909.16		38,834.03	
5	12,736.36	12,736.36		0.00	-38,172.80		46,742.31	
6	12,927.41	12,927.41		0.00	-25,245.39		54,039.50	
7	13,121.32	13,121.32		0.00	-12,124.07		60,772.81	
8	13,318.14	13,318.14		0.00	1,194.07		66,985.82	
9	13,517.91	13,517.91		0.00	14,711.98		72,718.73	
10	13,720.68	13,720.68		0.00	28,432.66	-0.29	78,008.65	
11	13,926.49	13,926.49		0.00	42,359.15	-0.18	82,889.80	

12	14,135.39	14,135.39		0.00	56,494.54	-0.11	87,393.77	
13	14,347.42	14,347.42		0.00	70,841.96	-0.06	91,549.71	
14	14,562.63	14,562.63		0.00	85,404.58	-0.02	95,384.50	
15	14,781.07	14,781.07		0.00	100,185.65	0.01	98,922.97	
16	15,002.78	15,002.78		0.00	115,188.44	0.04	102,188.01	
17	15,227.83	15,227.83		0.00	130,416.26	0.05	105,200.76	
18	15,456.24	15,456.24		0.00	145,872.51	0.07	107,980.70	
19	15,688.09	15,688.09		0.00	161,560.60	0.08	110,545.83	
20	15,923.41	16,923.41		0.00	178,484.01	0.09	113,061.39	

The modern protection systems contributes to reducing operational risks, minimizing equipment failures, and improving long-term infrastructure sustainability [13][21][22]. The performed technical and economical analysis demonstrates that the proposed investment is financially sustainable and technically feasible. The use of protection systems significantly improves operational continuity and infrastructure reliability and integrity [23][25].

4. Conclusions

The degradation of buried steel and reinforced concrete foundations are governed by complex interactions between environmental, electrochemical, and microbiological factors; soil properties directly influence corrosion kinetics and long-term structural performance.

Modern engineering approaches must adopt integrated corrosion mitigation strategies combining advanced materials, protective technologies, and predictive maintenance systems.

Future developments will increasingly focus on:

- sustainable corrosion protection materials
- advanced monitoring technologies
- predictive maintenance systems

These innovations are essential for reducing lifecycle costs while enhancing the resilience and reliability of underground infrastructure systems.

These findings suggest that foundation corrosion may represent a severely underestimated failure mechanism in aging 400 kV transmission lines.

From a power system perspective, the results suggest that foundation degradation caused by corrosion may represent an underestimated contributor to structural failure in aging transmission lines. In the case of 400 kV guyed towers, such mechanisms can gradually compromise stability and increase the likelihood of collapse under combined environmental and mechanical loading conditions.

Therefore, the integration of corrosion monitoring, predictive maintenance strategies and targeted rehabilitation measures should be considered a priority for transmission system operators aiming to improve long-term infrastructure resilience and reliability.

Author Contributions

Conceptualization, C.P. and M.M.; methodology, C.P.; validation, C.P. and M.M.; formal analysis, C.P.; investigation, M.M.; writing—original draft preparation, C.P. and M.M.; writing—review and editing, C.P.; supervision, C.P. . All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

Data supporting the findings of this study are available upon reasonable request from the corresponding author.

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Conflicts of Interest

The authors declare no conflict of interest.

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