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Methods to Evaluate Corrosion in Buried Steel Structures: A Review

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Abstract: Around the world, there are thousands of metal structures completely or partially buried in the soil. The main concern in their design is corrosion. Corrosion is a mechanism that degrades materials and causes structural failures in infrastructures, which can lead to severe effects on the environment and have direct impact on the population health. In addition, corrosion is extremely complex in the underground environment due to the variability of the local conditions. The problem is that there are many methods to its evaluation but none have been clearly established. In order to ensure the useful life of such structures, engineers usually consider an excess thickness that increases the economic cost of manufacturing and does not satisfy the principles of efficiency in the use of resources. In this paper, an extended revision of the existing methods to evaluate corrosion is carried out to optimize the design of buried steel structures according to their service life. Thus, they are classified into two categories depending on the information they provide: qualitative and quantitative methods. As a result, it is concluded that the most exhaustive methodologies for estimating soil corrosion are quantitative methods fed by non-electrochemical data based on experimental studies that measure the mass loss of structures.

Keywords: soil corrosion; steel structures; metal construction; qualitative methods; quantitative methods

1. Introduction

Engineering projects often require the use of metal structures partially or completely buried in the soil. As a result, millions of tons of underground steel constructions are found throughout the world. For instance, such structures include tanks, foundations, or pipes that cross countries to transport water, natural gas, and hazardous liquids from their sources to customers [1]. In fact, most of the total energy consumed in developed countries goes through an oil pipeline somewhere between its original source and the final point of consumption.

The main concern related to the useful life of buried steel structures is corrosion [2]. Corrosion is the degradation of the steel that ends up causing the failure of the infrastructure [3,4]. It is an essential factor in the design phase of such infrastructures, not only for its implications in structural resistance but also for its importance in economic calculation, as it implies costly maintenance in the phase of exploitation [5,6]. Because of corrosion, metallic buried structures must be regularly inspected, maintained, and occasionally replaced [7,8]. Furthermore, the failure of these structures presents serious risks to human health and the environment [9–11]. For instance, when a foundation fails, it is possible that the structure that it supports also fails or leads to the leakage of dangerous substances which can trigger dangerous explosions [12–14].

Corrosion has always been a concern in the field of engineering due to its severe consequences on structures [15,16]. In the case of buried steel structures, the risk of corrosion of steel comes from the surrounding conditions [17]. To describe the corrosion behavior of a material, we must adequately identify the environment to which it will be subjected. The existing literature evidences that its study has been mostly focused on the corrosion of metals under atmospheric conditions.

In this environment, most materials present predictable mechanisms of corrosion, which are highly dependent on the level of pollution, relative humidity, and temperature. Once these basic parameters have been identified, steel corrosion is expected be common in similar climatic zones. On the contrary, in the soil the situation is very different. The underground environment is characterized by a huge variability in the local conditions of soil chemistry, conductivity, humidity, etc. [18,19]. Moreover, it is also influenced by external factors such as precipitation and artificial manipulation of the soil. All of these factors have a significant effect on how steel behaves in each type of soil. Despite the difficulty involved in studying the behavior of ferrous metals in an environment as complex as the soil, it is essential to know their behavior in the field of engineering. A large amount of the steel produced in the world is bound for the construction of metal structures that are going to be buried; therefore, it is necessary to investigate the effect of corrosion in underground environments in order to achieve the correct and optimal design of such metal structures.

In financial terms, corrosion in buried steel structures represents real economic and environmental problems [20,21]. The high cost of corrosion has been known for years; Uhlig conducted a study in 1949 that revealed that the cost of corrosion was equivalent to 2.5% of the U.S. Gross Domestic Product (GDP) [22,23]. In 2016, National Association of Corrosion Engineers (NACE) International published a document about the costs of corrosion, estimating that in 2013 the global cost of corrosion was $2.5 trillion, which is equivalent to 3.4% of the global GDP. As a solution to the problem, Koch et al. estimated that the use of corrosion control practices can save between 15% and 35% of the cost of corrosion in structures [24].

In the design of buried steel structures, researchers seek to determine the adequate amount of steel according to the required guarantees that assure their agreed useful life. The precision in the design process allows for adjusting the tolerances. In this way, less material is required and the cost of fabrication decreases, which allows for the generation of more economically competitive tenders and the greater probability of success. In addition, the elimination of security thicknesses through optimal sizing allows for the design of infrastructures in accordance with the principles of sustainable engineering in terms of efficiency and the demand of materials. To achieve the optimal trade-off between security and the cost of buried steel structures, it is vital to provide the designers with optimal tools.

The problem is that no clearly established method exists to determine the sizing of the buried metal structure in the design phase [25]. The purpose of this paper was to conduct an exhaustive review of the existing methodologies to estimate the corrosion of steel in the soil, as this constitutes the main concern in the design of this type of infrastructure. If the engineers responsible for buried metal structure design know the existing tools as well as their fundamental principles, the parameters considered, and their field of application, this may help to ensure that their decisions in the sizing of the structure are objective and in accordance with the required useful life of the structure.

2. Corrosion in Buried Metal Structures

Corrosion is defined as the degradation of a material or its properties due to its reaction to the environment in which it is immersed [26]. It is a gradual destruction that normally affects metals, and it is produced by a chemical or electrochemical reaction with the environment that surrounds it [27]. According to Davis, soil corrosion may be considered to encompass all corrosion taking place on buried structures [28]. In 1989, Chaker and Palmer, who was president of Control Engineering, defined soil corrosion as the deterioration of metal or other materials brought about by chemical, mechanical, and biological action in a soil environment [29]. The situation in the soil is completely

different to other environments, such as the atmosphere. The complex variability of underground environments causes different soils conditions, even when they are geographically close. This factor greatly hinders the estimation of the sizing of the metallic structures that are going to be buried in the design phase.

Although this destructive force has always existed, it has not been considered until modern times because of the progress of general civilization and particularly of technology. Structures such as foundations or pipelines are just some of the many structures that have been affected by soil corrosion throughout the world over the years [30,31]. The degradation that occurs due to corrosion is the general cause of the alteration and destruction of a large part of natural and man-made materials. It is estimated that approximately 25% of annual steel production is destroyed by corrosion [32].

The corrosion of buried steel structures occurs when concentration cells are generated. This process takes place when a metal is in contact with soils of different characteristics or due to differences in the material. The current flows through the earth from the anodic area to the cathodic area and through the steel tube of the cathode area, until it again moves to the anodic area to complete the circuit [33].

In most cases, the portion of the structure that is in the most conductive soil acts as an anode and the part located in the ground with low conductivity acts as a cathode. The same soil acts as an electrolyte and the structure is the metallic contact that is necessary for a corrosion cell to be generated [34]. Corrosion occurs at the place where the current is discharged from the metal to the ground in the anodic areas. In the cathodic zones, the flow of current goes from the ground to the metallic structure, keeping the construction protected [35]. In the anodic area of the structure, the anodic reaction occurs and produces the loss of metal ions, that is, the corrosion of the metal. In the cathode, the cathodic reaction or reduction reaction occurs [36,37]. Depending on the soil, different cathodic reactions may occur. For instance, the electrochemical reactions that govern the anodic and cathodic reactions are influenced by the presence of bicarbonate [38]. In particular, the mechanism of corrosion reactions on the exterior surface of buried structures when exposed to hydrated conditions containing carbon transporting agents are as follows [39]:

$$Fe(OH_2) + HCO_3^- \rightarrow FeCO_3 + H_2O + OH^-$$
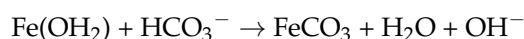
3. Corrosion in Soils

Soil is a very complex corrosive environment and, therefore, the corrosion of metals in this situation is extreme [40,41]. The cause of this instability derives from the constantly changing underground environment. In 1928, Logan determined that the degradation of a buried material is strongly dependent on the characteristics of the soil in which it is buried [42]. Most of the destructive processes that affect buried metals are of an electrochemical nature, mainly associated with the characteristics of the soils in which they are located [43,44]. The main factors that influence the corrosion of these infrastructures are listed as follows.

3.1. Soil Texture

Soil texture consists of the size distribution of the mineral particles that form the soil. The terrain is made up of clays (with diameters of less than 0.002 mm), silts (with diameters between 0.002 and 0.5 mm), and finally sands, exhibiting the largest particles (with diameters greater than 0.05) [45]. These particles are in turn are subdivided into thick, medium, and thin. Depending on the values taken by the percentages of sand, clay, and silt, the classification of the soil in different families is defined according to the ternary diagram shown in Figure 1.
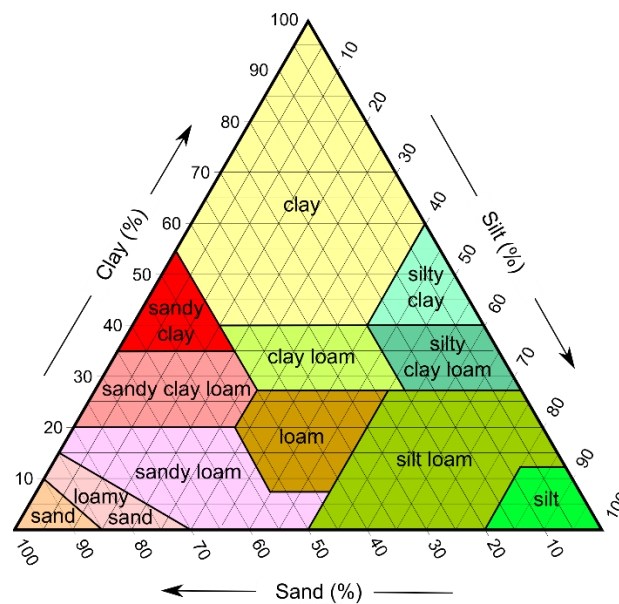
Figure 1. Ternary diagram of the soil composition [46].

The finer soil particles are considered the worst corrosive medium for buried steel structures. The mineral content of clay absorbs more water because it has more surface, so it is highly effective in the deterioration of metals [47–49].

3.2. Presence of Water

Water is a relevant parameter in assessing the corrosivity of soils [50]. In 1979, research showed a direct correlation between the mass loss in pipework and the moisture content of soils [48]. In 2015, the results of a study to evaluate the effect of soil moisture on corrosion confirmed its important influence on corrosion rates [51]. The reason for this is that liquid water represents the essential electrolyte for electrochemical corrosion reactions. Therefore, factors such as soil moisture, water retention capacity, groundwater level, and water mobility in the soil must be taken into account.

3.3. Aeration

In neutral or alkaline soils, the concentration of oxygen has a significant effect on the degree of corrosion because of its participation in the cathodic reaction. However, in the presence of certain bacteria corrosion can be very high, even under anaerobic conditions. It is worth mentioning that excavations can highly increase the degree of soil aeration [52]. It is generally accepted that the corrosion rate in disturbed soils with high oxygen availability is significantly higher than that in soils that have not been modified.

3.4. Redox Potential

Redox potential is essentially a measure of the degree of aeration of the soil: a high redox potential indicates a high level of oxygen. The value of soil redox potential depends on the dissolved oxygen content in the pore water and provides some information about the conditions in which the reducing bacteria of the soil could grow sulfate [53,54]. Low values of redox potential may suggest that conditions are favorable for anaerobic microbiological activity [55].

3.5. pH

In 2004, Oguzie led a study on corrosion in which it was suggested that buried metallic structures are susceptible to corrosion at any pH value [53]. However, a project carried out by Tibu and Oliveira

considered that pH is not a dominant factor in the corrosion mechanism when the soils have a pH in the range between 4 and 8.5 (a common range in soil) [56]. Despite these contradictions, research on this field of corrosion coincides with the fact that more acid soils have a much higher risk of corrosion in structural materials such as steel. On the other hand, alkaline soils tend to have high concentrations of magnesium and calcium, which often form deposits on buried surfaces with protective properties against corrosion.

The most widespread method for measuring pH is through pH papers based on color changes. The paper is moistened with the solution that is being measured and the color is compared with the established color standards.

3.6. Resistivity

Due to the relationship between corrosion and conductivity, resistivity has been considered the main variable to study in the field of soil corrosivity [57]. As the flow of ionic currents is associated with corrosion reactions, highly resistive soils tend to retard their effects [58,59]. The soil resistivity generally decreases with the increase in water content and the concentration of ionic species [60]. It is important to note that resistivity alone is not enough to evaluate the risk of corrosion, so its usefulness as the only absolute indicator is very limited [61].

Soil resistivity may be measured by a few traditional techniques such as the Wenner four-pin method or, more recently, by electromagnetic measurements [62]. Measurements of resistivity can be made both in situ and at the laboratory. However, Ferreira identified that laboratory resistivity measurements sometimes do not correlate well with field results [20].

3.7. Ions Content

The chemical components most related to corrosion are chlorides and sulfates. Chloride ions are generally harmful because they participate directly in the reactions of anodic dissolution of metals [63]. In addition, its presence tends to decrease soil resistivity. Chlorides may be present in soils naturally or come from external sources, such as the spillage of salt on roads in winter. The concentration of chloride ions is prone to significant variations depending on the degree of soil moisture [48,64]. As for the corrosive effect produced by sulfate ions on metals, it is lower than chlorides. However, its risk increases with the possibility that the sulfates become highly corrosive sulfides due to the activity of bacteria that can lead to the reduction of anaerobic sulfate [65,66].

3.8. Bacteria

Sometimes corrosion may be produced by the presence and activity of microorganisms [67]. The properties of the organic matter and the carbonate content that the soils present have relevant implications in the steel corrosion process [68–70]. This could appear as the result of clay soils rich in humus, which are very cohesive and inhibit the formation of an anticorrosive surface layer on the metallic object, something that other soil environments allow. There have been cases of extremely rapid corrosion rates due to bacterial activity, and it has become increasingly evident that the clear majority of metal alloys are susceptible to this type of corrosion. Several research studies have shown that microbiological corrosion is one of the causes of failure in pipes buried in the most harmful soils [71–73]. It has been quantitatively established that more than 20% of the failures that occur in pipes are related to microorganisms [74,75]. In 2009, a study estimated that this process constituted approximately 20% of corrosion costs to many industrialized countries [76].

Due to the relevance of microorganisms in corrosion, the term Microbiologically Implanted Corrosion (MIC) emerged, which refers to the phenomenon in which corrosion is initiated and or increased by the activities of microorganisms [77]. The first MIC case was identified in 1934, where sulfate-reducing bacteria (SRB) resulted in the failure of cast iron pipes buried in anaerobic soil [78]. Since this observation, numerous works have been written concerning the effects of bacteria [79].

After analyzing the parameters of the soil that affect corrosion separately, it can be deduced that the corrosion of steel in soil is a complex phenomenon, with a multitude of variables involved [30,80]. Each of those parameters influences the corrosion of buried metallic structures. Table 1 describes each of the variables studied as well as their relation to the degradation mechanism.

Table 1. Relationship between soil parameters and corrosion.

Variable	Relation
Soil texture	Direct
Presence of water	Direct
Aeration	Direct
pH	Inverse
Resistivity	Inverse
Redox potential	Direct
Ion contents	Direct
Bacteria	Direct

In the above table, the relationship of each variable with corrosion is shown independently. However, a soil environment implies the iteration of all of these variables, which simultaneously and severely affect buried metallic structures. Therefore, the corrosion that occurs in steel in this environment is not a consequence of a single parameter, but it is a phenomenon produced by the iteration of many different factors that influence degradation [81]. It is very important to emphasize that soil parameters do not work alone, but rather each variable affects and is influenced by the others, as shown in Figure 2.
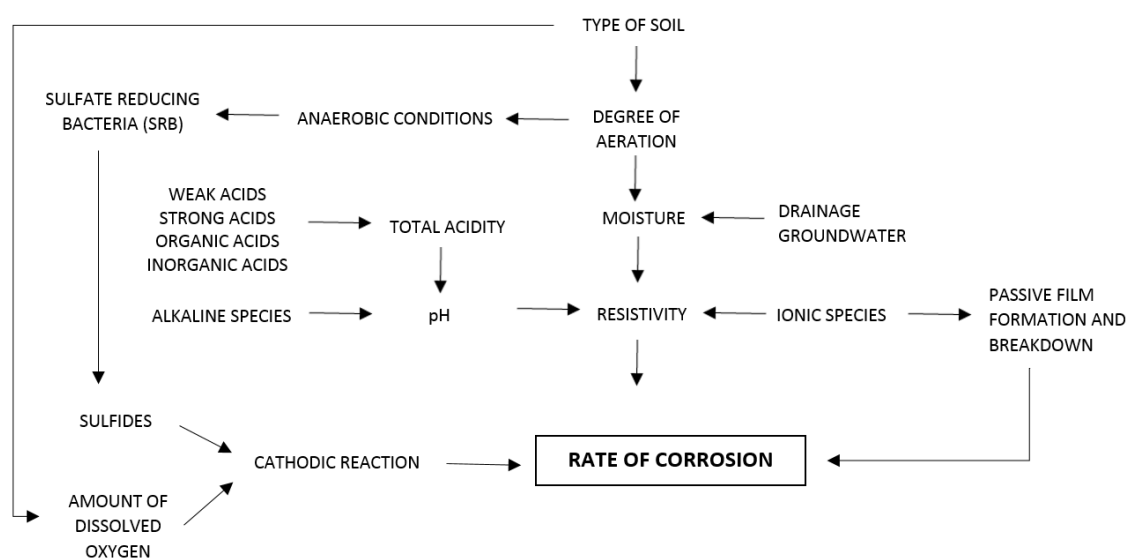

Figure 2. Relationship of variables affecting the rate of corrosion in soil.

In summary, it is important to note that corrosion is a consequence of the iteration of different factors characteristic of the local conditions of each soil type. Therefore, considering the complexity of the parameters that affect the corrosion and the high interrelations between them, it is obvious that it can be highly dangerous to employ approaches based on estimating the effect of soil corrosion through simplified solutions that only consider a few variables of the many involved.

4. Methods to Estimate the Corrosion of Soils

Once the mechanisms that intervene in the corrosion of steel in the underground have been studied, the next step is to analyze the existing methods to estimate the consequences of corrosion in each type of soil. The aim is to predict the behavior of the structure when it is buried in soil according to its local characteristics and thus realize its definition in the design phase depending on its service life.

4.1. Type of Data

The typology of the data used in corrosion tests may be divided into two broad categories: electrochemical and non-electrochemical.

As a consequence of the electrochemical nature of the corrosion processes, the inputs based on electrochemical principles are widely used throughout the spectrum of corrosion engineering [82]. The main variables that are measured in an electrochemical test are the voltage and current as well as, to a lesser extent, the impedance and electrochemical noise [83]. Potential refers to the voltage of the corroding electrode measured at an open circuit in an electrolyte. Current or current density is usually related either to the corrosion rate or to some features of the corrosion process, such as surface redox reactions that can change the corrosion characteristics. Polarization resistance is another parameter related to the corrosion rate and it is inversely proportional to the corrosion current [84].

Among the most outstanding methods used to measure the electrochemical characteristics aimed at orienting or quantifying corrosion is the conductivity method, which was first reported in 1937 for the direct determination of corrosion in the laboratory [85]. Two years later, Logan conducted a study where he expressed the limitations of the tests by concluding that comparisons between experience and predictions carried out in the laboratory are often unsatisfactory, as it is difficult to reproduce all of the factors that are involved in a testing room [86]. In 1955, a new method appeared to measure the potentials of polarized electrodes in soil corrosion cells [87]. This method was an improvement over a method designed by Hickling and was applied by Denison and Darnielle [88,89].

Although the electrochemical factor is a key parameter in metallic corrosion, most of the tests performed to evaluate the corrosion of buried metal structures are not based on measuring the current or voltage. The non-electrochemical data are focused on directly assessing the corrosion experienced by buried steel by means of samples in specific terrains or in simulated environments in the laboratory. Even images of real situations in equal environments must be considered as data that can be used to establish corrosion calculation models.

The mass loss of a metal is one of the most common non-electrochemical tests to estimate the corrosion rate. This technique involves placing a metal specimen in an underground environment for a fixed period. Before introducing the sample into the ground, its weight is defined and, after the prescribed time, it is unearthed and reweighed. The difference between both measures is the mass loss by corrosion. Another non-electrochemical parameter that is used is so-called localized corrosion. This consists of a mixture of qualitative observations and quantitative measurements of soil characteristics that give rise to a global view of corrosion. In practice this turns out to be a process involving data from both field experience and laboratory research [90].

Corrosion is an extremely complex mechanism that the result of the action of a set of diverse characteristics, which must be calculated before defining the models that are used in the sizing of metal structures buried in the design phase. According to the dataset that feeds the model, this practice will make the designed models more reliable. Baboian established distinct levels of reliability of corrosion data in his book, *Corrosion Tests and Standards* [84]. The lowest level corresponded to the use of data obtained from the general literature, followed by data obtained in laboratories including electrochemical tests, data obtained in similar situations, and finally data obtained from the same characteristics.

Both electrochemical and non-electrochemical data are used to calculate the dimensions of this type of structure, and all of the data can be used in methodologies that may be grouped into two broad categories based on the information they offer: qualitative methods and quantitative methods. On the one hand, qualitative methods give guidance on predicted future corrosion without assigning numerical values to the expected corrosion. On the other hand, quantitative methods provide a value that expresses the expected corrosion rate. The latter are often based on field trials and allow for the calibration of elements to focus on the required useful life of the structure.

4.2. Qualitative Methods

The qualitative methods of estimation of corrosion provide information on the corrosive capacity of soils based on the main variables by which they are defined. The more parameters the model considers in estimating the interval of corrosion, the greater its reliability. The main benefit of these models is that they usually consist of tables or diagrams with easy format and management. This simplicity that allows agile use of the tool also triggers its principal disadvantage, as it does not grant a numeric value. Thus, the engineer who uses this type of technique obtains information about the rate of corrosivity of the soil that will affect the buried metallic structure, but it is the designer who decides the thickness of the structure. Consequently, it is a method strongly subjected to the interpretation of each of its users. From orientations that can go from a non-corrosive to an extremely corrosive soil, the engineer defines the level of protection of the structure.

When corrosion began to be recognized as a concern in engineering, numerous qualitative methods emerged. At first, scientists linked the corrosion of buried structures to a single parameter and made tables that related the rate of soil corrosion to this variable. They focused their studies only on the factor that they considered to have the most relevant role in the mechanism of degradation of the structure.

Due to the historical importance of resistivity in terms of its performance in the corrosion of metals, there are several tables that relate the resistivity of the soil to the degree of corrosion [91]. The most widely used methods to assess aggressiveness were put forth by NACE and American Society for Testing and Materials (ASTM), which are summarized in Table 2 [92–94]. These types of tables are easy and fast to use but their main problem is that they only consider one parameter, the resistivity of the soil. Therefore, its applicability is very limited in the design phase of buried metallic structures.

Table 2. Corrosivity ratings based on soil resistivity according to American Society for Testing and Materials (ASTM G187-12a: Standard Test Method for Measurement of Soil Resistivity Using the Two-Electrode Soil Box Method) and National Association of Corrosion Engineers (NACE).

Soil Resistivity (Ω.cm)	NACE	ASTM
>10,000	Negligible	Very mildly corrosive
5001–10,000	Mildly corrosive	Mildly corrosive
2001–5000	Mildly corrosive	Moderately corrosive
1001–2000	Moderately corrosive	Severely corrosive
501–1000	Corrosive	Extremely corrosive
0–500	Very corrosive	Extremely corrosive

In 1946, Starkey and Wight developed a model relating the corrosion in soil to the redox potential [95], as shown in Figure 3.
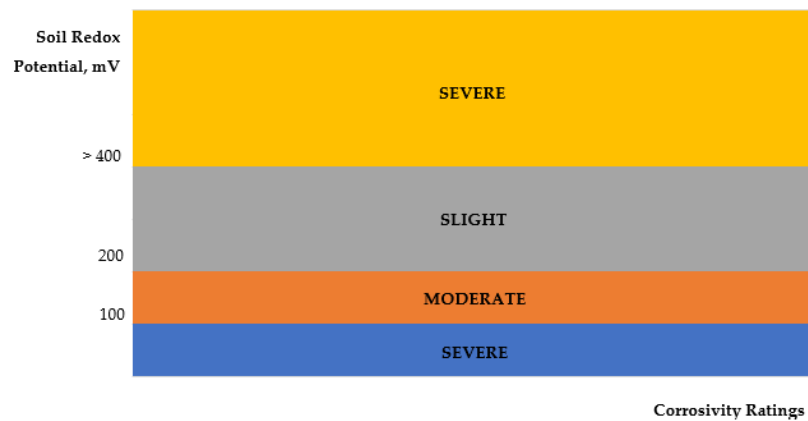
Figure 3. The relationship between soil corrosivity and the redox potential.

In the same univariate approach, other researchers considered pH to be the key factor in the corrosion process [53]. Some models provide an approximate relationship between the pH of the water extract of the soil and its corrosivity, for instance that shown in Figure 4.
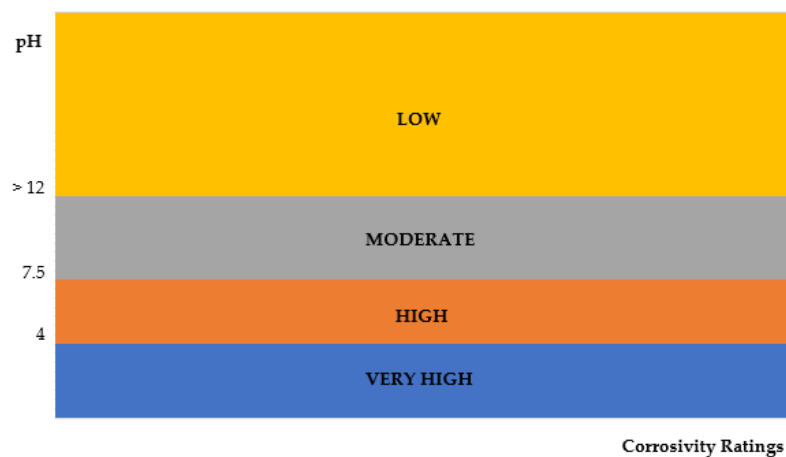

Figure 4. The relationship between soil corrosivity and the pH.

Soon, scientists realized that the mechanism of corrosion in buried structures is the result of the iteration of many factors, and it was dangerous to consider only one. As a result, researchers began to create qualitative models that relate the corrosivity ratio to more than one variable. In 1963, Pourbaix represented corrosion in diagrams depending on the potential and the pH (Figure 5). These diagrams were called Potential-pH diagrams or Pourbaix diagrams, after their creator. This approach offers a great amount of thermodynamic information in an agile and efficient format. However, although it incorporates two variables in the study of corrosion, it still does not consider the numerous factors that intervene in the corrosion phenomenon [96].
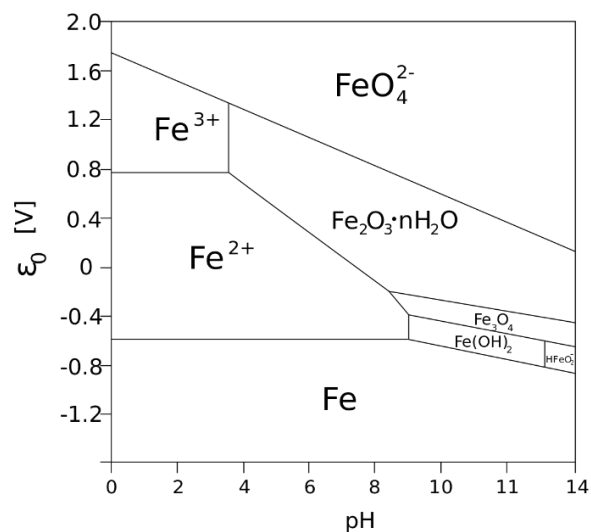
Figure 5. Porbaix diagram for iron. Credit to Andel Früh [97].

A relevant and extended model to estimate corrosion was developed in the European standard. EN 12501-2:2003 on the protection of metallic materials against corrosion [98]. The standard provides a qualitative estimation of corrosive soil taking into account two variables: pH and resistivity. This method suggests some guidelines for determining the corrosion load on soils. Its limitation is due to the fact that it only establishes three different levels of corrosion: high, medium, or low, as shown in Table 3.

Table 3. Corrosive soil load function of pH and resistivity according to EN 12501-2:2003.

pH	Resistivity (Ω.cm)	Corrosion
<3.5	Any	High
3.5–4.5	<4500	High
	>4500	Medium-High
4.5–5.5	<4500	High
	4500–5000	Medium-High
	>5000	Medium
5.5–6.0	<1000	High
	1000–5000	Medium-High
	5000–10,000	Medium
	>10,000	Medium-Low
6.0–9.5	<1000	High
	1000–3000	Medium-High
	3000–10,000	Medium
	10,000–20,000	Medium-Low
	>20,000	Low

The multivariate approaches are generally based on point scales. These types of methodologies consider the most important variables in the corrosion process, giving them a score based on the characteristics of the soil in which the metal structure will be buried. In addition, each parameter has a different weight depending on its rate of affection to corrosion. In this way, not only a higher number of variables is taken into account than in the previous methods, but also the severity of the parameter in the corrosion of the metal is considered. One of these methods is the soil corrosivity scale, applicable to steel developed by the American Water Works Association (AWWA). It includes a strict ranking system generated by the assignment of a global score composed of points depending on each variable

(Table 4). In general, the method assumes that resistivity, pH, and redox power are the most important factors in corrosion [99,100]. As in the other qualitative methods studied, there is no concrete measure of the loss of recommended material or values, but rather an orientation of the use of coatings or not. In this method, the soil corrosivity potential is divided into four categories: mild, moderate, appreciable, and severe [101]. The methodology is not intended to be definitive, but may be used, for instance, as a checklist to prioritize various inspection and maintenance tasks.

Table 4. Point system for predicting soil corrosivity.

Assigned Point	Resistivity (Ω.cm)	pH	Redox Potential (mV)	Sulphides	Moistures
0	>3000	4–8.5	>100	Negative	Good drainage
1	2500–3000				Fair drainage
2	2500–2100			Trace	Poor drainage
3		2–4			
		>8.5			
3.5			50–100	Positive	
4			0–50		
5	2100–1800	0–2	<0		
8	1800–1500				
10	<1500				

Even though the most widespread method in corrosion engineering is the AWWA, there are more techniques that follow this approach of assigning points to different variables that intervene in the corrosion mechanism. In 1960, another qualitative approach with similar characteristics was developed by the German Association of Engineers of Water and Gas Works (DVGW), which reflects the different factors that affect corrosion to provide an indication of the type of soil with respect to the corrosion [102]. This basic method was modified by the Eyre and Lewis approach [103], which in turn was reviewed and adopted by the Motorways Agency in the UK for use in a design manual for roads and bridges [104]. Another similar technique is the Deutsches Institut für Normung (DIN) 50 929 standard, which is an update of the DVGW procedure [105]. Part three of this DIN normative provides a methodology that has been validated in many different projects [106].

More recently, other examples of qualitative methods have been defined based on the assignment of scores. Among these is a method developed by the American Iron and Steel Institute in 1994, by Pritchard et al. in 2013, or by Roberge in 2016 [36,107,108]. The latter was developed through an extensive soil evaluation program that was carried out in Europe. It resulted in the production of a worksheet method for estimating the probability of corrosion damage to metallic structures in soils [109]. The worksheet consists of 12 individual ratings (R1 to R12), as described in Table 5. This methodology is very detailed and comprehensive. The summation of the individual ratings produces an overall corrosivity classification; scores less than −10 indicate a highly corrosive soil and positive values (>0) indicate a non-corrosive environment. Sea- or lakebeds cannot be assessed using this worksheet [110].

Table 5. Variables considered in the Dechema Soil Corrosivity Worksheet.

Rating Number	Parameter
R1	Soil type
R2	Resistivity (Ω)
R3	Water content (%)
R4	pH
R5	Buffering capacity
R6	Sulphide content (mg/kg)
R7	Neutral salts (mmol/kg)
R8	Sulphates (mmol/kg)
R9	Groundwater
R10	Horizontal homogeneity
R11	Vertical homogeneity
R12	Redox potential

The most modern approach in qualitative methods is to introduce new technologies in the treatment of information obtained from existing methods. The Design Decision Model is a qualitative model that converts the recommendations obtained in the AWWA point system into a risk matrix. This model considers in the axis of abscissa factors of plausibility that are the 10 points described in AWWA C-105 (Table 4), and in the axis of ordinates the factors of consequence. In this way, it is possible to arrive at a new vision that relates the operational reliability and the difficulties that may exist, affecting maintenance and repairs. By entering the graph at the appropriate points, there is intersection that establishes the appropriate recommendation for corrosion mitigation (Table 6) [111].

Table 6. Design Decision Model(x: likelihood and C: consequences).

Likelihood	Consequences	Proposed action
<10	Any	Standard protection
10–20	<30 $1035.7x^{-1.05} > C > 240.25x^{-0.7}$ $>1035.7x^{-1.05}$	Standard protection PE (Polyethylene) PE+bonded joints
20–35	<25 $1596.1x^{-1.08} > C > 1035.7x^{-1.05}$ $>1596.1x^{-1.08}$	PE (Polyethylene) PE+bonded joints PE+bonded joints or Cathodic protection
35–40	<30 $1177.8x^{-0.89} > C > 1596.1x^{-1.08}$ $>1177.8x^{-0.89}$	PE+bonded joints PE+bonded joints or cathodic protection Cathodic protection
40–45	$<1177.8x^{-0.89}$ $>1177.8x^{-0.89}$	PE+bonded joints or Cathodic protection Cathodic protection
45–50	Any	Cathodic protection

Over time, qualitative methods have evolved with scientific discoveries regarding soil corrosion and the variables that affect them. In the beginning of the study of the soil corrosivity, scientists opted to evaluate one or a few variables that were considered the most important. Later, the research community understood that the corrosion mechanism is the sum of many factors and their iteration. The numeric scales enhanced the tables and initial diagrams and, with the development new technologies, improved their application and the number of factors considered. However, these are techniques capable of providing recommendations on corrosion, without numerical values of the loss of material that the metal will experience. Therefore, qualitative methods are subjective depending on the interpretation of the engineer responsible for the design of the buried structure, as there is no value to support their decisions. Their purpose is to offer an orientation for the possibility of corrosion and, therefore, its application during design phases is very restricted.

4.3. Quantitative Methods

Quantitative methods for the assessment of corrosion in buried metal structures are those that provide a numerical value with respect to the corrosion. A quantitative estimate of what will be the rate of corrosion is an essential tool with undoubted utility to engineers who design buried metal structures. In this sense, it is possible to decide the structure dimensions to guarantee the useful life that is required from an objective view. Most of these types of methods are fed by field data, enabling engineers to size the structures according to the useful life that is required in each project.

The most complete quantitative studies conducted to date with reference to the corrosion of steel in different types of soils were carried out by Romanoff for the National Bureau of Standards of the United States between 1910 and 1955. They are considered to be the most important studies in the history of corrosion engineering due to the duration of the exposure, the large number of samples that were studied in different types of soil, and the fact that it was an experiment performed in a real environment. Between 1922 and 1952, thousands of metal samples were buried and exposed in

numerous underground sites in the United States [112]. The accumulated corrosion data were compiled by Romanoff in a final report, published in 1957, which represents the basis of all existing knowledge in this field. The results of the project contain data tables where the information related to corrosion is exposed (both in terms of mass loss and maximum depth of penetration) for the different materials and coatings used as well as for each of the floors studied (Figure 5) [113]. The data provided by these tables should be interpreted with caution, because there are several relevant limitations. The fact that the tests were conducted almost a century ago is the most obvious restriction, since sampling and analysis techniques at that time did not reach the minimum quality levels that would be required today.

Romanoff was the first scientist to revolutionize the field of underground corrosion of steel. His studies established the bases that still govern global ideas of how corrosion attacks buried structures. Until then, there was very little knowledge about the mechanisms and evolution of steel corrosion in underground applications. Most subsequent investigations only confirmed the conclusions and recommendations provided by this work. The research carried out by Romanoff consisted of burying several pieces of different qualities of steel in soils for long periods of time, from months to several years, to discover how the corrosive soil affected the pieces. The experiment, in its entirety, lasted 20 years and was developed in different places in the United States. Romanoff tried to determine if soil properties could be used in order to predict corrosion. Romanoff classified corrosive factors under the four headings of aeration, electrolytes, electrical factors, and miscellaneous, with the last group containing man-made alterations to the natural soil environment as well as the effect of bacteria [114].

To ensure the applicability of the results of the study, a large number of soils with different characteristics were selected. These soils were analyzed to determine their physical, chemical, grain size, and climatic characteristics. In each of the places, several samples (mainly pipes) of different types of steel, both bare and coated, were buried. Periodically during the duration of the tests, the samples were excavated (two by two) and taken to a laboratory where scientists evaluated their loss of mass. Thanks to this, it was possible to evaluate the behavior of corrosion in steel buried in the soil for different time periods.

In 1988, National Bureau of Standards (NBS) became National Institute of Standards and Technology (NIST), and published a study titled: "Analysis of Pipeline Steel Corrosion Data from NBS Studies Conducted Between 1922 to 1940 and Relevance to Pipeline Management" [115], with a detailed analysis of the information contained in Romanoff's work. The relevance of this study in the field of soil corrosion is evident, given its completeness, the reliability of the source, and the fact that it is relatively recent. In it, a series of deficiencies identified in the original tests are described, including:

- Poor statistical design of the experiments. The statistical analysis was not a highly valued part and, consequently, measurement procedures were not developed.
- It did not consider variations in the horizons of the soil. As a result, pipes buried in the same trench but at opposite ends could be exposed to very different conditions.
- Seasonal and annual variations were not contemplated due to the use of annual average values for some variables (temperature, precipitation, etc.). In addition, the exposure times and dates of the initiation of the experiments varied from place to place. The exact dates of burial and extraction of the samples are unknown, which is significant because corrosion damage can be concentrated in certain seasons. A sample with an exposure time of one year and three months can present a much higher degree of corrosion than a sample with an exposure time of one year, because the first has endured the most problematic season twice.
- Different depths of burial. At each site, the experiments were carried out by the most common methods of burial, instead of applying the same procedure of preparation of the experiment throughout the study, which introduces more uncertainty into the dataset.
- Use of unrepresentative values for some variables. For example, the average rainfall used corresponds to the nearest place with available data, and the information corresponds to the historical average instead of the burial period of the trial. Therefore, the effect of particularly rainy years is unknown.

- Many properties were measured in the laboratory instead of on site. The alterations generated in the soil by eliminating the samples influence the activity of water, carbon dioxide, oxygen, etc. It also influences the pH, so that these measures incorporate an inherent error.
- Incomplete information about the chemical analysis. Due to budgetary limitations, only a complete chemical analysis was performed on 26 of the 47 initial trial sites. In addition, the choice of these 26 sites did not follow any random sampling procedure, but those with lower resistivity were chosen.
- It did not consider the possible changes in soil conditions over time. Human activity, for example, could have changed the conditions in any of the sites during the years of the experiment, but there is no information about it.

In addition to these limitations due to the test procedure and the techniques used, there are a series of conditions related to the applicability of the results. On the one hand, the alloys used in the study differ significantly in their composition from those commonly used nowadays. On the other hand, Romanoff's own study concluded that the quantitative application of the results must be done carefully and be restricted to the area near the sites where the trial was developed.

Despite the established limitations, it is an indisputable fact that these data are still used today in many applications. There has not been another investigation as exhaustive as Romanoff's that can replace the data obtained in his study. He did investigate a second small set of samples to complete the previous cases [116]. These experiments were much shorter than those conducted by NIST, generally limited to a maximum of three years. Consequently, the results taken from tests of such short duration are considered less representative than the original NIST, which in some cases reached 17 years.

Other similar studies have been conducted to bury steel samples in soil and dig them up to calculate their mass loss and therefore evaluate their corrosion. For instance, Ikechukwu et al. in 2014 developed a model to predict corrosion in buried steel structures from the evaluation of four different soils where four steel samples were buried. The project selected four different soil types and transported samples to a laboratory where the steel was buried and the mass loss in each of the terrains was studied. Unfortunately, the research was carried out in a simulated environment and the number of samples was very small in relation to the Romanoff study [117]. In addition, this type of method only investigates a few soils, in this case only meeting the local characteristics, so it is very difficult to extrapolate the results to other locations.

The relationship between corrosion in structures buried in the ground and electrochemical phenomena results in electrochemical tests have also been used as a basis for feeding quantitative models of corrosion. In 1961, Stratfull published a paper in which he presented a new method to estimate corrosion in the soil. The technique consists of a graph that relates the corrosion rate of buried steel to the minimum soil resistivity and the influence of pH (Figure 6). The results of this new model were compared with the soil corrosivity determined by the reported weight loss of steel samples. It was concluded that the new test is a reasonable general indicator of the relative corrosivity of the soil [118]. The limitations of the method can be summarized in the idea that it considers very few parameters to estimate the underground corrosion rate.
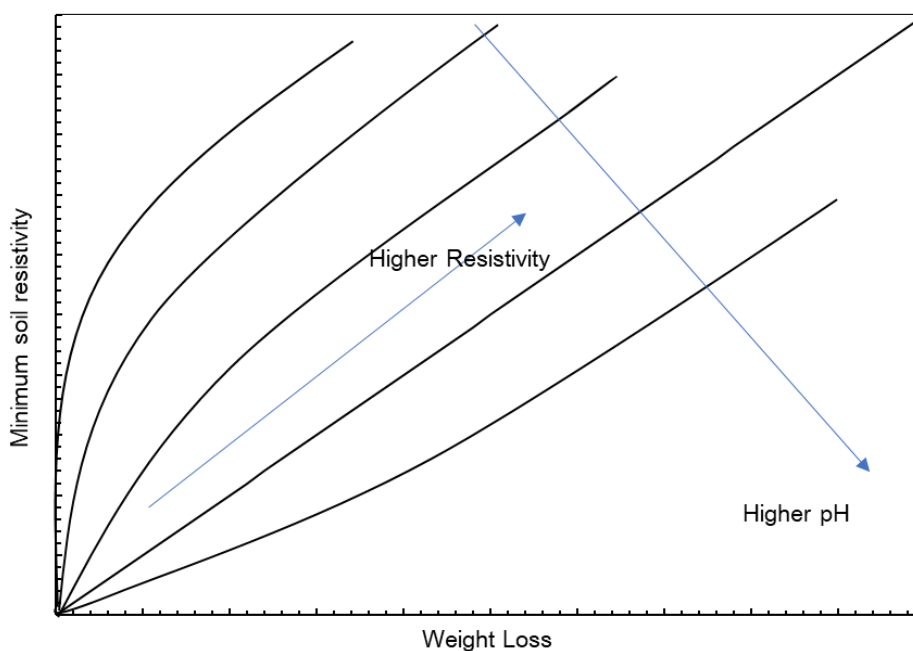
Figure 6. Relationship between minimum soil resistivity and underground corrosion rate.

Some investigations were recently carried out with the aim of predicting and quantifying the corrosion of underground structures. Most of them focused on the research of corrosion monitoring during the use of the piece or structure [119,120]. With these methods, it is possible to estimate corrosion from on-site measurements, being very useful for maintenance work, but they do not help in designing structures. Another approach studied the effect of a few variables on corrosion, such as the research of Nguyen et al. that investigated the corrosion rate from moisture and polarization [121]. However, it is well known that the final corrosion is due to the combined effect of several factors, so these types of simplifications are not very useful when designing structures.

Obtaining a quantitative method that relates a type of soil to the loss of material of a buried steel element is extremely complex. Experiments have been attempted in the laboratory in an effort to extrapolate findings to a quantitative model, but the results have not always been satisfactory.

4.4. Assessment of the Methods

Both qualitative methods and quantitative methods are used daily in the sizing of buried metal structures. On the one hand, the qualitative methods, as described in Table 7, are divided according to the variables used for the orientation of the degree of corrosion and the methodology used. Models based on point scales stand out because they not only consider a greater number of variables but also consider the weight of each one of the factors in the soil corrosion mechanism. Of those reviewed here, the most widely used method for assessing the corrosion of buried metal structures is that established by AWWA C-105.

On the other hand, quantitative methods are divided into two approaches, those based on field tests and those that feed the model through tests in simulated environments (laboratory). All of them share the aim of measuring the loss of mass of material; however, the problem is that the investigations are almost always based on very specific soils and with durations that usually do not exceed three years. Consequently, a more representative and extended method, such as the Romanoff Tables explained in Table 8, has not been developed in the recent past.

Table 7. Example of Romanoff's Table.

Soil		Duration of Exposure	Loss in Weight			Maximum Penetration		
No.	Type		Open Hearth Iron	Wrought Iron	Bessemer Steel	Open Hearth Iron	Wrought Iron	Bessemer Steel
		Years	oz/ft²	oz/ft²	oz/ft²	Mils	Mils	Mils
52	Lake Charles clay loam	2.0	3.1	3.4	2.7	66	62	40
		5.4	14.7	14.6	13.5	116	123	118
		7.5	19.0	19.0	16.9	116	176	163

Table 8. Evaluation of qualitative and quantitative methods.

Model	Type	Description	Methods	Soil Factors
Qualitative	Univariate	Direct Relationship	NACE ASTM	Resistivity Resistivity Soil redox potential pH
	Multivariate	Direct Relationship	Pourbaix diagrams EN 12501-2:2003	Potential, pH Resistivity, pH
		Point scales	AWWA C-105	Resistivity, pH, redox potential, sulfides, moisture
			DVGW	Soil composition, ground-water level at buried position, resistivity, moisture content, pH, sulfide and hydrogen sulfide, carbonate, chloride, sulfate, cinder and coke
			DIN 50929	Soil type and extent of contamination, resistivity, pH, moisture, soil condition (disturbed/undisturbed), buffer capacity, combined chloride/sulfate content, sulfate content, sulfide content, presence of ground water, vertical/horizontal homogeneity, external stray current
			Dechema Soil Corrosivity Worksheet	Soil type, resistivity, water content, pH, buffering capacity, sulfide content, neutral salts, sulfates, groundwater, horizontal homogeneity, vertical homogeneity, redox potential
		Risk matrix	Design Decision Model	Resistivity, pH, redox potential, sulfides, moisture
Quantitative	Multivariate	Field data	Romanoff Tables	Aeration, electrolyte, electrical factors, miscellaneous (man-made alterations, bacteria)

5. Conclusions

The corrosion that occurs in metal structures when buried in the ground is a major concern to engineers responsible for projects that require their design. All of the investigations collected in this paper on the estimation of damage caused by corrosion in metal structures buried in the ground have been classified according to whether they correspond to qualitative or quantitative methods. It has been concluded that, in the design phase of the structures, qualitative methods provide an orientation of the possible effects of corrosion, but do not provide a value that helps in sizing. Meanwhile, quantitative methods establish a greater exhaustivity and loss of subjectivity in the interpretation of the sources of information by the engineers in charge of the design phase of the project.

In addition, it has been shown that the severity of corrosion is the result of the combination of a large number of factors and the study of its effects depending on the individual behavior of a single variable can cause very serious errors in the design of structures and in the guarantees of their useful life. It is worth mentioning that the complexity of the soil can cause the same steel structure to cross different types of soil both in depth and in length. In this case, the designer must analyze each underground environment according to the models studied in this paper and opt, in general, to choose the most unfavorable conditions for the design.

Of all the investigations collected in this study, the most important source of information that is used to assess the corrosion that affects the metal elements in different underground environments is still that collected by the American NIST on the corrosion suffered by steel. It is a quantitative and multivariable method that has not yet been replaced by any other methodology. In spite of the limitations that it presents, fundamentally for having been published in 1957, it has the most complete database of test results on the corrosion of metals in soil.

Therefore, it is possible to optimize the design of metallic elements buried in construction projects using models that provide quantitative estimates of the corrosion they will experience in the soil.

After the revision of the existing methods used to study corrosion, it has been determined that the most reliable, despite its deficiencies, are the Romanoff Tables.

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