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Abstract: Metallic corrosion can cause substantial damage at various levels and in almost all types of infrastructure. For metallic corrosion to occur, a certain external environment and the presence of corrodents are the prerequisites. Stray current-induced corrosion, however, is a rather underestimated issue in the field of corrosion and civil engineering. Stray current arising from power sources and then circulating in metal structures may initiate corrosion or even accelerate existing corrosion processes. The most frequent sources of stray current are light rail transits and subways, which are also main traffic tools with continuously accelerating urbanization all over the world. Stray currents from these systems may easily flow into nearby metallic structures, making stray current-induced corrosion the most severe form of damage of buried structures, such as tunnels, pipelines, and various underground reinforced concrete structures. The objective of this paper is to critically review stray current-induced steel corrosion in infrastructure with regard to sources of stray current and the characteristics and mechanism of stray current corrosion in view of electrochemical aspects. The methods and techniques for the evaluation, monitoring, and control of stray current-induced corrosion for steel and reinforced concrete structures are also presented and discussed.

Keywords: electrochemical aspects; steel in infrastructure; stray current corrosion.

1 Introduction

1.1 Corrosion of steel in infrastructure

Corrosion, from the Latin “corrodere”, means “to chew away” or “to attack” a material as a result of chemical and/or physical interaction between this material and its environment. Corrosion is not limited to metals only but affects other materials as well (glass, wood, polymers, ceramics, etc.), which also corrode or degrade during their service life (Landolt, 2007). The subject of this paper is the corrosion of metals, particularly steel, which is a main construction material for infrastructure worldwide. Additionally, from more than 60 categorized corrosion types, as recognized in the field of corrosion science and engineering (Vandelinder, 1984), the topic of this work is electrochemical corrosion, specifically stray current-induced steel corrosion.

Most metals and alloys, when in contact with their surrounding medium such as atmosphere or water, tend to convert to a more thermodynamically stable state by forming oxides/hydroxides on their surface. This process follows chemical and electrochemical reactions with the external environment. In the long term, these interactions or the corrosion process itself would lead to the degradation of metals and to the reduction of their functional properties.

Steel corrosion can be and often is the primary cause of damage to various types of infrastructure, such as steel bridges, reinforced concrete structures, pipelines, and marine platforms. It is estimated that corrosion destroys one quarter of the world’s annual steel production, which corresponds to about 150 million tons/year or 5 tons/sec (Landolt, 2007). A study in the United States calculated the direct cost of corrosion to be $276 billion, which corresponds to 3.1% of the U.S. gross domestic product (GDP) in 2002 (Koch et al., 2002).

Corrosion damage is not always visible to the public but nevertheless can lead to structural failure, loss of life, loss of capital investment and environmental damage (Koch et al., 2002). Therefore, as more and more aging infrastructure reaches the end of its designed lifetime, the emphasis in the field of civil engineering today is on maintaining and extending the service life of valuable assets.

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To fulfill this, the control of steel corrosion must be considered and implemented.

Due to low cost and ease of forming at ambient temperatures, reinforced concrete is the most widely used construction material and forms an important part of infrastructure worldwide. The synergy of both materials (i.e. concrete and steel) provides a combination of high compressive strength and high tensile properties. Therefore, reinforced concrete is a composite material of global use and serves a variety of applications. Although reinforced concrete is considered to be of high durability, it can suffer from various degradation mechanisms related to either concrete or steel.

The corrosion of steel reinforcement has been identified as the main reason for reduced service life of reinforced concrete structures. With proper construction work and adequate maintenance of a civil structure, steel corrosion would be theoretically minimum during the overall designed service life. However, the penetration of aggressive substances as well as the combination of environmental factors and exploitation conditions result in premature degradation of reinforced concrete structures due to steel corrosion. The results are structural failure and enhanced health and safety risks.

Steel reinforcement in reinforced concrete is normally in a thermodynamically stable state. Steel passivity is due to the high alkalinity of the concrete matrix and concrete pore water, respectively (pH of 12.5–12.9). Additionally, concrete acts as a physical barrier: well-consolidated and properly cured concrete with an optimum water-to-cement (w/c) ratio has a low permeability and acts as a barrier against the penetration of corrosion-inducing substances, such as chloride ions or carbon dioxide (CO_2; Ahmad, 2003). The high electrical resistivity of the concrete matrix, through blocked or disconnected pore pathways, impedes the steel corrosion rate by simply restricting ionic or electron flow, hence contributing to the reduction of oxidation or reduction reactions on the steel surface.

As aforementioned, reinforcing steel does corrode mainly because of (1) the carbonation of concrete bulk matrix and subsequent loss of alkalinity at the steel-concrete interface and (2) the presence of chloride ions in sufficient amounts in the vicinity of the steel surface.

Carbonation occurs when CO_2 from air penetrates the concrete matrix and reacts with calcium-bearing phases, such as calcium hydroxide [$Ca(OH)_2$] to form carbonates. In the reaction with $Ca(OH)_2$, calcium carbonate ($CaCO_3$) is formed. This reaction reduces the pH of the pore solution to as low as 8.0–9.0, at which level the passive film on the steel is not stable. In this situation, the passive film is destroyed and the uniform corrosion of the steel reinforcement is at hand.

Chloride ions penetrate into the concrete cover by diffusing through the pores or through cracks. When chloride ions reach the surface of the rebar and accumulate to a certain critical value (chloride threshold concentration), they damage the passive film and localized corrosion (pitting corrosion) will be induced (Jang & Oh, 2010). Irrespective of the factor responsible for corrosion initiation, once the passive film is destroyed, the surface of the corroding steel will function as a mixed electrode that is a "composite" of anodes (active areas) and cathodes (nonactive areas). The separation of anodic and cathodic areas on the steel surface results in a potential difference and triggers oxidation and reduction reactions. During the corrosion process, electrons flow from the anodic to the cathodic areas, whereas ions flow in the surrounding electrolyte (i.e. a corrosion cell forms). The concrete pore water functions as the aqueous medium (i.e. it serves as a complex electrolyte). As the corrosion process becomes stable, the anodic oxidation and cathodic reduction reactions will reach equilibrium (i.e. the potential of steel reaches equilibrium at the corrosion potential, E_{corr}), at which point the net exchange current is zero. The corrosion cell that forms on a rebar surface is shown in Figure 1.

The anodic reaction, or the oxidation process, results in the dissolution or loss of metal, whereas the cathodic reaction for reinforced concrete is mainly the reduction of dissolved oxygen, forming hydroxyl ions. For steel embedded in concrete, the following are the most probable anodic reactions (Ahmad, 2003):

$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^- \tag{1}$$

$$2\mathrm{Fe} + 3\mathrm{H_2O} \rightarrow \mathrm{Fe_2O_3} + 6\mathrm{H}^+ + 6\mathrm{e}^- \tag{2}$$

$$\mathrm{Fe} + 2\mathrm{H_2O} \rightarrow \mathrm{HFeO_2^-} + 3\mathrm{H}^+ + 2\mathrm{e}^- \tag{3}$$

$$3\mathrm{Fe} + 4\mathrm{H_2O} \rightarrow \mathrm{Fe_3O_4} + 8\mathrm{H}^+ + 8\mathrm{e}^-. \tag{4}$$

Depending on the availability of O_2 and the pH in the vicinity of the steel surface, the possible cathodic reactions could be as follows:

$$2\mathrm{H_2O} + \mathrm{O_2} + 4\mathrm{e}^- \rightarrow 4\mathrm{OH}^- \text{ (alkaline)} \tag{5}$$

$$2\mathrm{H}^+ + 2\mathrm{e}^- \rightarrow \mathrm{H_2} \text{ (acidic)}. \tag{6}$$

Once steel corrosion is initiated, it will proceed in time with various rates depending on the environment and relevant conditions. The corrosion products that form will accumulate in the proximity of the anodic locations.

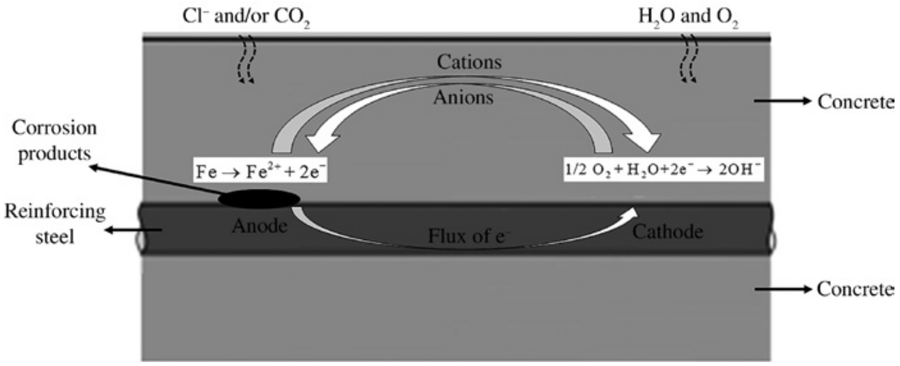


Figure 1: Schematic illustration of the corrosion of reinforcement steel in concrete.

However, these corrosion products have higher volume than the original steel itself (see Figure 2) and occupy a greater volume at the steel-concrete interface. Next, dissolution and precipitation mechanisms are responsible for the penetration of corrosion products in empty voids, cracks, and interfaces within the bulk matrix. The volume expansion itself induces internal stress, resulting in microstructural damage toward the concrete cover. Ultimately, concrete cover cracking and spalling will be at hand, leading to the exposure of the steel reinforcement.

Except for chlorides and reduced pH due to bulk matrix carbonation, other factors can also induce the corrosion of reinforcing steel in concrete. Although sulfates can hardly act as a major stimulator of corrosion in an environment containing chlorides, their presence in the proximity of the steel surface at even low chloride content may contribute to a higher corrosion rate (Baronio et al., 1996a, b). Microbiology-influenced corrosion (MIC) is a type of corrosion in which the deterioration of metallic as well as nonmetallic material occurs due to the presence and activities of microorganisms, such as bacteria, fungi and algae (Geweely, 2011; Usher et al., 2014). It is found that the major bacteria involved in MIC are sulfate-reducing bacteria (SRB), manganese/iron-oxidizing bacteria, iron-reducing bacteria, and acid-producing bacteria (Enning et al., 2012). These bacteria are commonly present in communities as biofilm and influence the electrochemical process as a consequence of their metabolic activity (Alasvand Zarasvand & Rai, 2014). MIC is a serious issue and challenge when steel-only structures are concerned, whereas concrete biodegradation is related to reinforced concrete, mainly affecting the concrete cover and bulk matrix. In other words, microorganism-induced reinforced concrete degradation accounts for a high level structural degradation of the cement-based material before any damage on the steel surface.

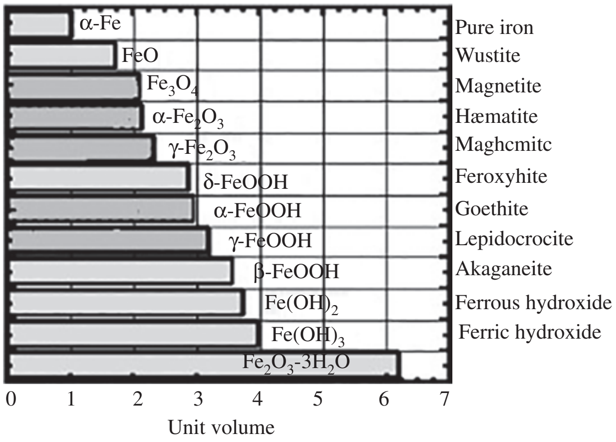


Figure 2: Corrosion products of iron (Jaffer & Hansson, 2009). Reprinted with permission from Elsevier.

1.2 Stray current-induced corrosion

Electric currents flowing along other elements, which are not components of the purpose-built electric circuit, are called stray currents. Stray current arising from power sources and then circulating in metal structures may initiate corrosion or even accelerate existing corrosion processes (Bertolini et al., 2007). However, stray current-induced corrosion is somewhat neglected or less reported, although the range of unwanted interactions of stray currents under favorable conditions is much broader than generally recognized.

Stray current can originate from electrified traction system, offshore structure, marine platforms, cathodic protection (CP) system, etc., and then can be picked up and conducted through many parts of infrastructure in close proximity or remote locations (reinforcement in concrete, buried pipelines, and tanks). In the case of stray direct current (DC) interference, a cathodic reaction (e.g. oxygen reduction or hydrogen evolution) takes place where the stray current enters the metallic structure, whereas an anodic reaction (metal dissolution) occurs where the current leaves the structure. Usually, this attack is localized and can have serious consequences on a metallic structure.

Stray current-induced corrosion is one of the most severe forms of damage to buried structures, such as tunnels and underground pipelines (Riskin, 2008; Chen et al., 2013). At the end of the 19th century and the beginning of the 20th century, when the technical revolution with the emergence of electric traction was launching, the world was confronted with accelerated corrosion due to stray currents (Lingvay et al., 2008). In 1887, the first serious case of stray current corrosion was reported in the United States from a tramway system operating in Brooklyn, affecting steel pipes. Similar cases of stray current corrosion, caused by tramway operation, were reported in 1893 in Great Britain and in 1916 in Melbourne. In 1904, the effects of stray currents from electric railways resulted in the corrosion of buried structures in Germany, and in 1910, the first guidelines for limiting stray currents from DC railways, to protect gas and water pipes, came into effect.

Later, with the intensive development of the petroleum and gas industry (about 8% of the world's production of metals is used in oil and gas production, transport, and processing), the corrosion of buried oil or gas pipelines, induced by stray current, has been found more and more frequently all over the world (Jiang et al., 2014).

Stray currents can also flow into and then circulate within reinforced concrete structures near a railway, initiate corrosion, or even accelerate existing corrosion processes on embedded reinforcement (Carmen et al., 2011; Duranceau et al., 2011; Solgaard et al., 2013). In 1906 and 1907, attention was given to the potential damage of reinforced concrete structures caused by stray currents from electric railways and other power sources in the United States.

Nowadays, with continuously accelerating urbanization all over the world, electrified traction systems (rail transit or subway) are becoming main traffic tools due to the faster speed and greater passenger travel capacity to relieve the traffic pressure. Various types of reinforced concrete structures may be subjected to stray current leaking from the rails, such as viaducts, bridges, and tunnels of the railway networks or structures placed in the neighborhoods of railways (Santi & Sandrolini, 2003; Chen et al., 2006; Sandrolini, 2013). In these cases, the concrete pore water acts as the electrolyte and the reinforcing bars (or prestressed steel wires) embedded in concrete can "pick up" the stray current. Compared to stray current-induced corrosion of a pipeline, the issue in reinforced concrete has relatively more problems to deal with: the volume of corrosion product gradually increases and the pressure induced subsequently around the embedded steel can compel surrounding concrete to expand up to possible cracking, spalling, or delamination, which will finally lead to the failure of the whole structure. Additionally, stray current can also affect the microstructural properties of the concrete matrix (Susanto et al., 2013; Aghajani et al., 2016). As it is difficult to rebuild or repair the structures under or near rail transits, this kind of corrosion of reinforced concrete structures is of course urgently in need of a more in-depth investigation and consideration.

In this paper, a critical review of stray current-induced steel corrosion in infrastructure, especially and specifically when they are near the electrified traction systems, will be presented from stray current characteristics to the mechanism of stray current corrosion. An introduction on the impact factors related to stray current-induced corrosion, means for stray current corrosion control, monitoring, or evaluation of stray current-induced corrosion risks, will be also presented and discussed.

2 Sources of stray current

2.1 Electrified traction system

In electrified traction systems, the current drawn by the vehicles returns to the traction power substation through the running rails. This path, besides forming part of the signaling circuit for the control of train movements,

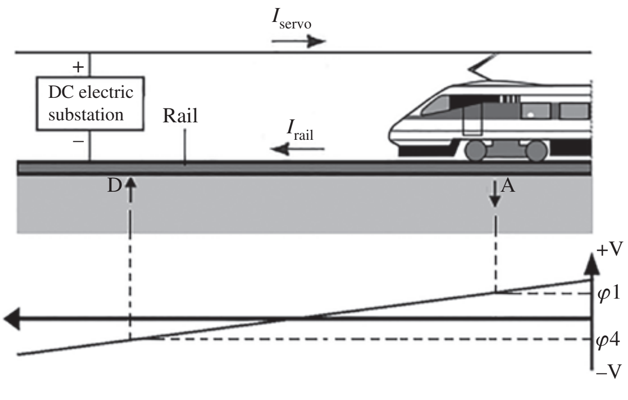


Figure 3: Schematic of rail-to-earth voltage profile for rail system (Bertolini et al., 2007). Reproduced with permission from Elsevier.

together with return conductors, forms the current return circuit path (Figure 3).

Although measurements are normally taken to avoid current leakage from railway systems, this is an inevitable occurrence. Owing to the longitudinal resistance of the rails (40–80 mΩ/km rail; Cotton et al., 2005), forming a voltage drop along the rail ($\varphi 1$–$\varphi 4$; see Figure 3) and their imperfect insulation to ground (typically from 2 to 100 Ω/km; Cotton et al., 2005), part of the return current leaks out from the running rails. It flows along parallel circuits (either directly through the soil or through buried conductors) before returning onto the rail, where the negative terminal of the substation forms the stray current (Sandrolini, 2013).

At the worst static case, the distribution of rail potential to earth and the leakage current level along with the rail has been evaluated by Charalambous and Aylott (2014). The result of this numerical simulation can be seen in Figure 4, showing that the level of leakage current was positively correlated with rail-to-earth voltage.

As any underground metallic structure has (in general) a lower electrical resistance than soil, the stray current can flow through it. Similarly, stray current would flow through the conductive portion of a reinforced concrete structure, which is the steel reinforcement. The example of stray current from a DC railway line picked up by steel reinforcement in concrete is illustrated in Figure 5.

From Figures 3 and 5, it can be seen that the returning current (I_{rail}) leaks out from point A of the rails, and then flows directly through soil and buried reinforced concrete, before returning into point D on the rail.

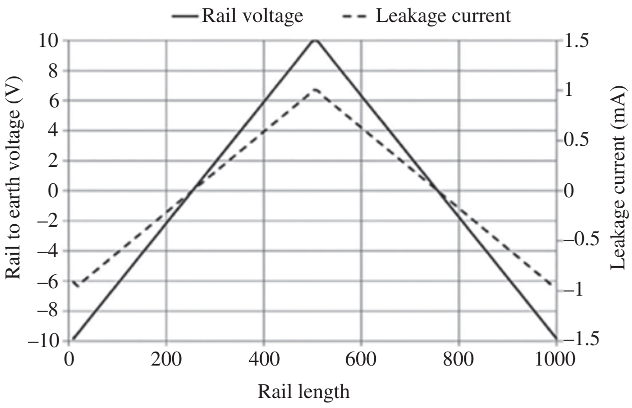


Figure 4: Simulated rail-to-earth voltage and leakage current (Charalambous & Aylott, 2014). Reprinted with permission from IEEE.

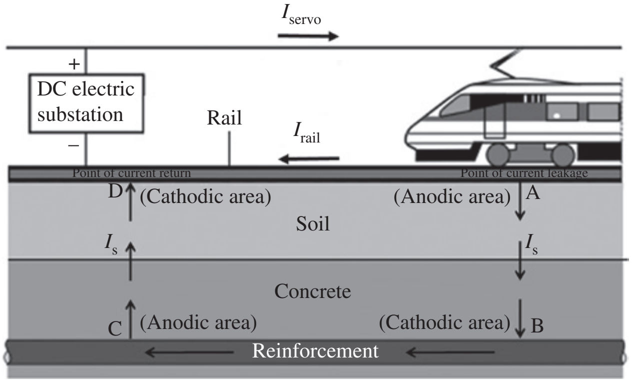


Figure 5: Example of stray current (I_s) from a DC railway line picked up by steel reinforcement in concrete (Bertolini et al., 2007). Reproduced with permission from Elsevier.

The distance between point A and D is denoted L_{rail} (m) as follows: $\varphi 1$ and $\varphi 4$ are the potentials at points A and D on the rail (Figure 3). For a resistance per unit length (r_{rail}, Ω/m) of rail, there will be a resulting voltage drop (ΔE) caused by the returning current in the rail along the distance L_{rail} of rail, consequently:

$$\Delta E = \varphi 1 - \varphi 4 = L_{\text{rail}} \cdot r_{\text{rail}} \cdot I_{\text{rail}}. \tag{7}$$

The salts deposited along the rail's base and flange generally contain chlorides and sulfates (Robles Hernández et al., 2009). Given that the current flow in a metallic conductor is an electron flow, whereas that through electrolytes such as soil and concrete, is ionic, it follows that there must be an electron to ion transfer as current leaves the rails and flows into the soil. Where a current leaves the rail oxidation occurs, a process is related to loss (or "production") of electrons. For the current to return onto the rail, there must be a reduction or electron-consuming reaction (Cotton et al., 2005).

Similar to the corrosion cell formed on reinforcement in concrete (Figure 1), there exists a dynamic equilibrium of anodic (oxidation) and cathodic (reduction) reactions, with the equilibrium potential of E'_{corr}. The schematic representation of the electrochemical cell, cathodic and anodic areas (points A and D) on a rail, is illustrated in Figure 3, in conditions when current leaks out and returns to the rail. Where the current leaks out from the rail (point A, with the area of A'_{a} and the anodic current density of i'_{a}), anodic area forms, where the corrosion of the rail's base can be significant and is as actually observed (Figure 6). When the current returns back onto track at point D, a cathodic current is present, with the area of A'_{c} and the cathodic current density of i'_{c}.

The relationship between them can be expressed as follows:

$$I_{\text{s}} = i'_{\text{c}} \cdot A'_{\text{c}} = i'_{\text{a}} \cdot A'_{\text{a}}. \tag{8}$$

Figure 6: Different views of a section of 100 lb rail showing severe corrosion at the base of the rail (Francisco & Gabriel, 2007). Reproduced with permission from the National Academies Press.

In addition to all above considerations and examples, it should be noted that current leakage from electric traction systems (rails) constitutes the major and most frequent cause of the induction of strong stray currents in specific industrial sectors (Miskiewicz et al., 2012). As a special case for this situation, the stray current issue in coal mining has also been attracting public attention (Peabody, 2001; Ma et al., 2010; Miskiewicz et al., 2012). The underground mining haulage systems (electric traction networks), operating in as much as the same manner described for railway transit systems, can also induce stray current and then lead to the corrosion of surrounding embedded metallic structures.

Besides the corrosion problem, in the most general case, the presence of stray currents in mining, particularly in underground excavations, may also produce the following risks: (1) hazards during blasting, possible accidental firing of the detonator, due to a stray current of sufficient intensity entering the circuit; (2) risk of explosion as result of stray voltages in intrinsically safe circuits or as a result of sparking, which can occur when two bodies under stray voltage are in contact; (3) fire danger as a result of the long-lasting flow of stray current, resulting in the ignition of coal dust or methane due to the local heating up to the ignition temperature; and (4) hazards to personnel or reduced production due to the failure of control systems and disturbances caused by the penetration of stray current (and stray voltages) into the control, monitoring, and warning circuits of mining equipment and devices (Miskiewicz et al., 2012).

In a mine, the knowledge of the true sources of stray currents and the hazards posed by their interaction is indispensable, particularly in prophylactic actions. Theoretically, most of the listed possible effects may occur simultaneously. Usually, however, in local mining practice, some of the causes and effects may be neglected.

2.2 CP system

Impressed current CP systems can cause stray current interference on adjacent metallic structures depending on the location of the ground beds, the exact location of the metal structure, and the operating characteristics of the CP system (Peabody, 2001). Any metallic structure buried in soil, for example, a pipeline or reinforcing steel embedded in concrete, represents a low-resistance current path and is vulnerable to the effects of stray currents.

One of the cases for this situation is illustrated in Figure 7: the current path originating from the components of the CP system flows through the soil (from the anode to the cathode; i.e. the metallic structure to be protected) and can be picked up by a low-resistance metallic object, as a pipeline. Determined by the soil resistivity, at least part of the current flown through the anode of this impressed current CP system will just flow into another conductor (the steel pipe nearby). Accordingly, in the current "pickup" region, the potential of the pipeline, subject to

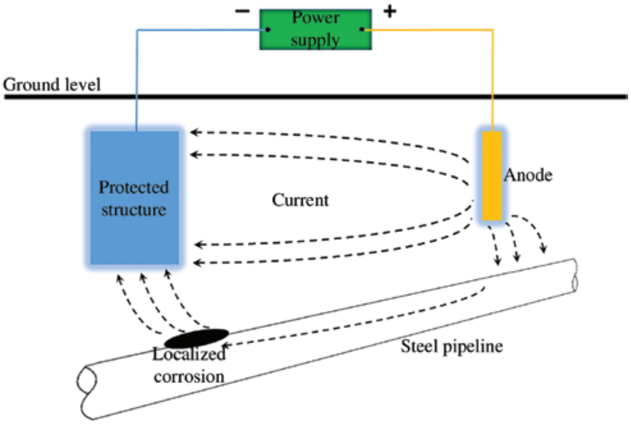


Figure 7: Schematic of stray current resulting from CP.

the stray current, will shift to the negative (cathodic) direction, whereas anodic polarization will be relevant for the portion of the pipeline, where the stray current leaves this structure. This would be the area with the highest risk of stray current-induced corrosion damage. In other words, the current supplied to the metallic structure under protection could deviate from its original path and act as a stray current source for a nearby structure (the pipeline), which is not part of the CP system. The existence of stray current was reported to reduce the efficiency of CP systems, as the current supposed to protect the intended structure would be attenuated (Jones, 1996).

Related to the above aspects on stray current induced by CP systems, the corrosion of the X52 steel pipeline was investigated by potential and pH measurements, weight loss measurements, and optical microscopy (Qian & Cheng, 2017). The pipeline was a nearby direct stray current flow originating from DC power supply. The tests were performed for various levels of DC densities. It is shown that the DC stray current could polarize, either anodically or cathodically, the steel at the anodic and cathodic zones, respectively, resulting in the accelerated corrosion of the steel and the cathodic reduction of dissolved oxygen. The CP potential was not maintained at the applied value under the DC interference and was shifted to positive and negative directions in the anodic and cathodic zones, respectively. In this case, the steel in the anodic zone cannot be protected, at least not fully protected. The result will be a reduced CP efficiency for the protected pipeline, as the on-potential (required for effective CP performance) was not maintained at the originally applied value in conditions of interference and occurrence of stray current.

2.3 High-voltage power lines

Municipal and industrial developments require the transport of considerable amounts of energy through long distances, which enhances the importance of the power lines as an essential link between energy generators and final consumers. Power lines supported by power towers with foundations can be found almost everywhere. In these systems, the high corrosion rate of the semi-underground foundations is usually detected. It is believed that corrosion results from stray currents that flow through the ground to close the loop between neighboring towers (Klunk et al., 2011). Stray currents here originate in the rod cables of the power line towers, induced by the strong electromagnetic and electric fields of the energized power lines (Wojcicki et al., 2003).

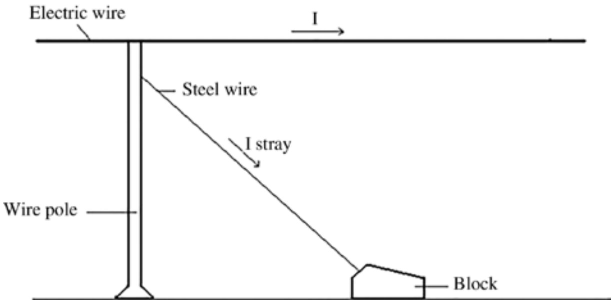


Figure 8: Schematic of the setup of block, steel wiring, wire pole, and electric wire.

This kind of stray current does not only attack buried foundations but also flows into the ground accessory structure near the power supply system. For instance, it is well known that a power supply system along a railway is necessary, and the electric wiring of this system in general is supported by wire poles. In 2017, a survey on soil corrosion of grounding grid for power substations in Hainan Island, China, was performed (33 substations, i.e. 11 substations of 35 kV, 17 substations of 110 kV, and 5 substations of 220 kV located in 17 regions of the island, were involved; Fu et al., 2017). The intensities of DC stray current for all the sites of substations were observed and measured, showing the existence of stray current-induced corrosion.

This installation is also found along railways (e.g. near Utrecht, The Netherlands; Beton, 2012). In this case, the wire poles are fixed by the steel wire connected to a reinforced concrete block (Figure 8). However, it is found that the anchors in the block used to connect the steel wiring and the reinforcement in the block suffer from corrosion at an extremely high level and rate. In some exceptional cases, the blocks with a design service life of 80 years were damaged totally only after 3 years due to steel corrosion and corrosion-induced cracks around the anchors (Figure 9). The rebars in the block were also corroded at different levels. According to the investigation (Beton, 2012), the corrosion damage here was also induced by stray current from the electric wiring.

2.4 Disturbances of the earth’s magnetic field

Occasionally, varying potential and current distribution of buried structures will be encountered in areas where there is no known source of “manmade” stray current. These variations are usually associated with disturbances in the earth’s magnetic field: a voltage is generated on a buried

Figure 9: Damaged block due to the corrosion of anchor induced by stray current.

metallic structure (for instance, a pipeline) due to the variations in the earth's magnetic field along the pipeline route. Stray current induced by transient earth's geomagnetic activity is also termed telluric. Telluric effects may be identified with recording instruments and are classified into quiet, unsettled, and active conditions.

Such disturbances have been found most active during periods of severe sun activity (Peabody, 2001; Roberge, 2012). Fortunately, although occasionally intense, telluric current effects on buried metallic structures are seldom of long duration and may not even be localized at specific pickup or discharge areas for any length of time. For this reason, corrective measures are not often required. Should areas be found, however, where the condition occurs frequently enough and is of serious intensity, corrective measures should be adapted to counteract the telluric effects.

2.5 Stray current underwater

Although the occurrence of stray current in water is much less probable than in the ground, stray current has also been found underwater (Lenard & Moores, 1993). Owing to the relatively low conductivity of freshwater, compared to seawater, stray currents from identical source are less dangerous in the former case and with a potentially higher risk in the latter case (Riskin, 2008).

Stray current in marine environment can come from welding operations, inadequate electrical systems, and boats with different grounding polarities (Lenard & Moores, 1993). For instance, when the grounding current of a boat flows through water to the ground point, another nearby boat could provide a path of lower resistance. Once part of grounding current flows through the boat as stray current, the corrosion of the boat's hull will be induced. More specifically, the anodic areas, where oxidation occurs, will be location where the current leaves the hull and flows into the surrounding water, whereas the cathodic areas will be the location where the stray current "enters" the boat.

Another example of stray current corrosion underwater is illustrated in Figure 10. A welding motor generator located on shore, with grounded DC lines to a ship under repair, can cause a serious damage to the hull of the ship by current returning from the welding electrodes through the ship and through the water to the shore installation. In this case, it is better to place the generator on board of the ship and bring alternating current (AC) power leads to the generator, as AC currents leaking to ground cause less stray current damage (Revie, 2008; Kolar & Hrbac, 2014).

2.6 Electrolyzers and bus ducts

Special standards exist for determining the stray current reduction measures in reinforced concrete structures of electrochemical plants of the chemical and metallurgic branches of industry. Electrolyzers and bus ducts are the major stray current sources in these plants. Overlaps, platforms for the maintenance of electrolyzers, columns and beams for supporting bus ducts, as well as underground structures of reinforced concrete are the objects of the attack by stray currents (Riskin, 2008).

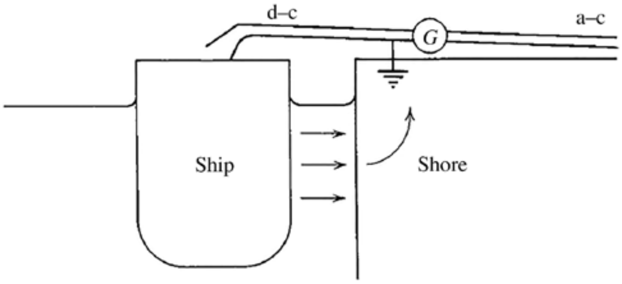


Figure 10: Stray current damage to a ship by a welding generator (Revie, 2008). Reprinted with permission from John Wiley & Sons, Inc.

2.7 Other sources

It is reported that stray currents have been also found elsewhere, and in some situations, these other causes may also be of importance. They may include (1) communication networks and control and warning circuits; (2) means of communication using radio transmitters; (3) local galvanic cells, which are formed by metallic masses in wet compartments; (4) static electricity; (5) atmospheric discharges; and (6) spontaneous polarization-induced electric fields by ferroelectric materials (Miskiewicz et al., 2012).

It is clear that, irrespective of the source of stray current, once nearby metallic structures exist, stray current could be conducted through these structures, as they represent a low resistance path. Stray currents will enter the metallic structure and then leave to the surrounding soil or water, and stray current-induced corrosion or the acceleration of the existing corrosion on these metallic structures will occur.

3 Characteristics of stray current

Depending on the stray current sources, a classification is made into stray DC or stray AC, with different frequency (for AC), continuity, fluctuation and current density.

For instance, as one of the most common stray current sources, railway electrification system may induce different kinds of stray current. As shown in Figure 11, a variety of traction powers are being adopted in European countries (Smulders, 2013). Consequently, the stray current arising from these electrified traction systems may be stray DC or stray AC, where both can induce the corrosion of nearby metal structures. It should be noted that although the effects of AC stray current are more complex in the sense of more characteristic parameters, AC interference is known to be much less dangerous than DC (Radeka et al., 1980).

Unlike industrial platforms that produce stray currents with a relatively stable intensity in time, the stray currents produced by electrical tractions are fluctuating in both intensity and duration (Faugt, 2006; Lingvay et al., 2008). Stray currents derived from the electrical traction system may fluctuate over short or long intervals of time, parallel to the varying load of the power source. This is also in contrast to galvanic or CP currents, which are relatively stable.

Figure 12 presents results from potential fluctuations in the discharge area of a pipeline, subjected to stray current due to its proximity to a transit system. The chart shows that the pipeline is affected by stray current activity when the transit system is in operation, especially during the morning and afternoon rush hour periods (Peabody, 2001). In the Chen et al. (2013) study, it

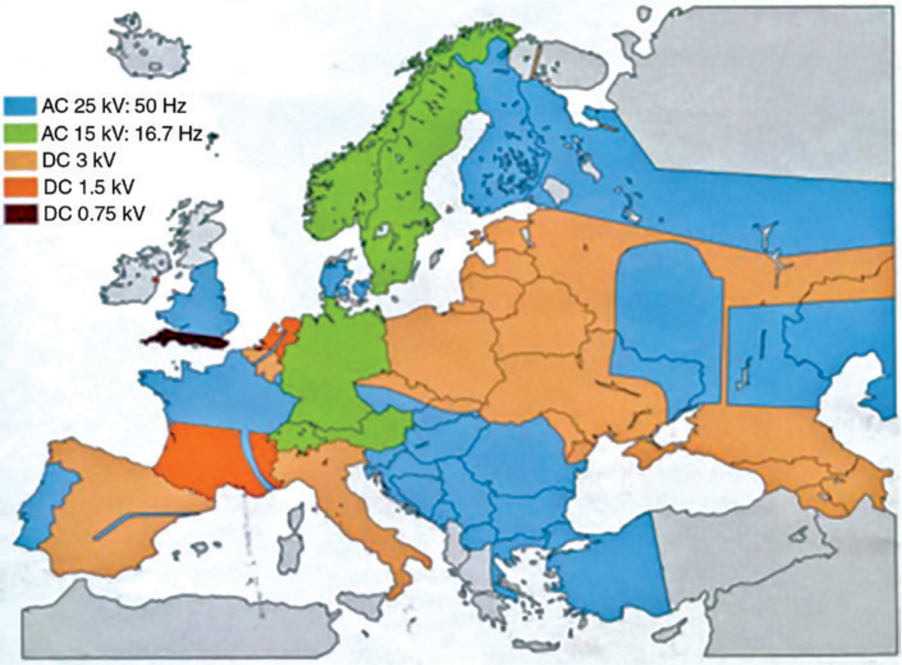


Figure 11: Distribution of traction power for railways in Europe (courtesy of Elektrische Bahnen). Reprinted with permission from Elektrische Bahnen.

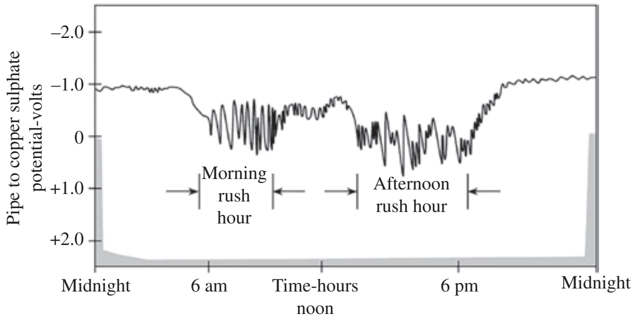


Figure 12: Pipe-to-earth potential at traction system stray current discharge area (Peabody, 2001). Reproduced with permission from NACE International (Houston, TX).

is also found that stray currents produced by rail traction systems are nonstationary, and the effect of interruptions of stray current should be taken into account in some particular situations.

For instance, when detecting dynamic stray current interference by the structure-to-electrolyte potential, the measurement duration should be long enough to make sure both platforms and fluctuations can be captured. Additionally, to evaluate stray current corrosion risk accurately, the obtained potential fluctuations must be carefully handled (Zakowski & Darowicki, 2005). To this aim, a new detection method has been proposed by Darowicki and Zakowski (Darowicki & Zakowski, 2004; Zakowski & Darowicki, 2005). This method employs short-time Fourier transformation (STFT). This method of analysis allows the determination of signal spectral power density changes (e.g. structure potential) in the function of time. In the paper, results have been presented regarding the total time-frequency analysis of a pipeline potential in a stray current field generated by a tram traction.

It should be also noted that a variety of factors can affect the stray current interference and the possibly induced corrosion on a later stage. The ohmic drop (IR component) occurring due to the resistance between the working electrode and the reference electrode are always involved during potential shift measurement in practice, especially in reinforced concrete due to the relatively higher resistivity of the concrete matrix surrounding the steel rebar. This kind of undesired signal (burdening of the measurement as a results from the IR component) usually leads to uncertainties and even overestimations of stray current corrosion evaluation of pipelines (Zakowski & Darowicki, 2001, 2003; Darowicki & Zakowski, 2004). In this case, the dynamic behavior of the IR drop itself should be also considered in the presence of unstable stray current interference.

4 Corrosion of steel induced by stray AC

Corrosion caused by stray AC was first reported back in the early 1900s (Jones, 1978; Radeka et al., 1980; Pagano & Lalvani, 1994; Song et al., 2002; Kim et al., 2004, 2006; Lazzari & Pedeferri, 2006; Fu & Cheng, 2010; Büchler, 2012; Chen et al., 2013; Li et al., 2013; Jiang et al., 2014; Wang et al., 2014; Zhu et al., 2014a–d). It is found that stray AC-induced corrosion is much more moderate than stray DC: in the experiments conducted by Radeka et al. (1980) on ship construction steel, AC-induced corrosion damage is at the level of 4.35% to 17.57% of the equivalent densities; other researchers estimated that for metals, such as steel, lead, and copper, AC causes less than 1% of the damage caused by an equivalent DC current (Revie, 2008; Kolar & Hrbac, 2014).

In practice, it is not easy to predict stray AC-induced corrosion rate by considering parameters such as alternating induced voltage. This, for example, is the case of a pipeline survey, where it was reported that the most rapid corrosion did not always occur at the points of the highest induced alternating voltage (AV) on the pipeline (Hanson & Smart, 2004; Goidanich et al., 2010). The relationship between AC density, frequency of AC, and corrosion rate has been studied and reported and will be summarized below.

In terms of stray AC-induced corrosion, the higher the density of stray AC with the same frequency is, the more serious the corrosion damage will be. Specifically, based on experimental results on carbon and low alloy steels in free corroding condition (Bolzoni et al., 2003; Goidanich et al., 2004, 2006), what can be concluded is as follows: when the AC density is higher than 100 A/m^2, an increase of corrosion rate by a factor of 2–5 is determined. The higher the AC density is, the larger is the corrosion rate. No significant corrosion rate was observed in various environmental conditions (e.g. both aerobic and anaerobic) at AC density lower than 30 A/m^2. Therefore, most authors suggested an AC critical current density of 30 A/m^2 (Bolzoni et al., 2003; Goidanich et al., 2004, 2006, 2010; Ormellese et al., 2010), above which corrosion will be significant.

It should be noted that coated structures are more susceptible to AC-induced corrosion than bare ones. A particularly harmful situation is when parallelism is associated with the use of high dielectric coatings, such as extruded polyethylene or polypropylene, as an extremely high AC density can be reached at the coating pinholes or small defects (Santi & Sandrolini, 2003; Revie, 2008; Goidanich et al., 2010; Ormellese et al., 2010; Jiang et al., 2014). This is because such high anodic current density, localized at a small area of defects, can further lead to the propagation of corrosion damage.

The influence of various AC current densities on the stress corrosion cracking (SCC) behavior of pipeline steel was also investigated (Wang et al., 2014; Zhu et al., 2014a,b). With increasing level of AC current density, the susceptibility to SCC increases. The AC current-induced additional corrosion damage was reported to affect the mechanism of SCC as follows: in the absence of AC, the fracture mode is intergranular and the mechanism is attributed to anodic dissolution. When AC is involved, crack propagation is transgranular, and the mechanism is mixed controlled by both anodic dissolution and hydrogen embrittlement. Besides, the thermal activation created by AC current was also considered to play an important role in AC corrosion (Gummow et al., 1998).

Corrosion induced by AC currents was reported to be more detrimental at the lower AC current frequency (Radeka et al., 1980). A set of experiments was conducted by Pagano and Lalvani (1994) at various frequencies (5–500 Hz). The relationship between average corrosion rates (for 24 h experiments) of mild carbon steel and the frequency of applied AV was established. It was discovered that, with increasing frequency from 5 to 500 Hz (with the same AV of 1000 mV), there was a sharp drop in the corrosion rate from about 7.5 to about 0.8 g/cm^2/year.

Overall and based on reported studies, it can be concluded that stray AC-induced steel corrosion increases with the increase of current density at constant frequency but decreases at a constant current of increasing frequency (Jones, 1978; Radeka et al., 1980; Pagano & Lalvani, 1994; Song et al., 2002; Kim et al., 2004; Fu & Cheng, 2010; Carmen et al., 2011; Zhu et al., 2014a–c). These studies also indicated that the AC corrosion of steel was only a fraction of that, which is otherwise induced by an equivalent level of DC. Due to the above considerations, the next sections of this paper focus mainly on DC-induced corrosion.

5 Mechanism of stray DC-induced steel corrosion in reinforced concrete near railway

5.1 Electrochemical conditions of reinforcement in concrete subjected to stray current

As aforementioned, for steel embedded in concrete, reactions at the anodes and cathodes are broadly referred to as anodic and cathodic half-cell reactions, respectively, as illustrated in Equations (1) to (6). The anodic reaction is the dissolution or corrosion of steel, whereas, for the cathodic reaction, the most likely reaction is Equation (5). Because, in concrete, oxygen is usually able to penetrate through the pores and microcracks in the proximity of the steel surface and the overpotential for oxygen reduction reaction is low, this reaction is the prevailing cathodic reaction. So what will happen when stray current is present and picked up by reinforcing steel rebar?

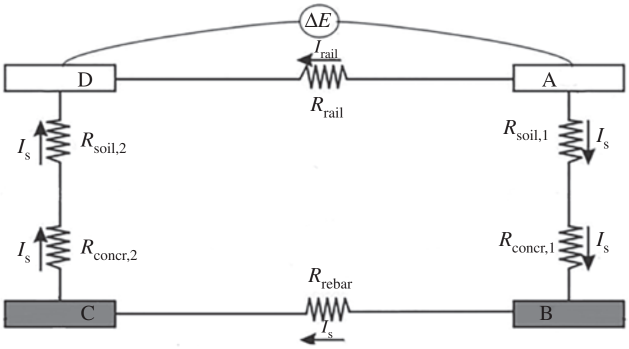


Figure 13: Equivalent electrical circuit to the scenario shown in Figure 5.

The concept of stray current in relation to reinforcement is already illustrated in Figure 5, where stray current originates from an electrified DC railway line, finds an alternative path through the soil and concrete, and then is picked up by the reinforcement if appropriate conditions are present (the requirements for the current to be picked up by reinforcement will be described later in Section 5). The closed equivalent electrical circuit relevant to this scenario is shown in Figure 13.

Where R_{rail}, R_{rebar}, $R_{soil,1}$, $R_{soil,2}$, $R_{concr,1}$, and $R_{concr,2}$ are the electrical resistances of the rail, reinforcement, soil, and concrete cover/matrix at different positions; I_s is the stray current flowing into the reinforcement. In this case, the supply voltage, ΔE is raised by the potential difference between points A and B on the track, where the stray current leaks out and returns back, respectively. Of course, depending on the different types of stray current source, the supply voltage for stray current varies.

Interference from stray current, flowing through surrounding soil and concrete matrix, may impose a significant effect on the electrochemical reactions, occurring on the surface of the reinforcement in underground concrete structures. Depending on the direction (sign) of the current, the electrochemical reactions stimulated by stray currents and their effects are as follows:

At the point where the stray current enters the reinforcement (cathodic area or point B in Figure 14), the

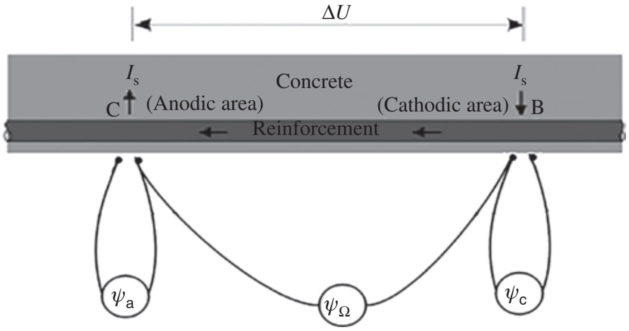


Figure 14: Schematic representation of the electrical interference on reinforcement in concrete.

anodic reaction is depressed and the cathodic reaction dominates (generally oxygen reduction for this environment). This results in cathodic polarization (ψ_c). In general, this will be beneficial (protecting steel), except for extreme cases where alkali-silica reaction (ASR) and the loss of steel/concrete bond might be stimulated as potentially detrimental side effects.

The anodic reaction (metal dissolution) occurs where the stray current flows out from the reinforcement (anodic area or point C in Figure 14) because of anodic polarization (ψ_a) induced by current outflow. This means that the process of corrosion is accelerated and the cathodic reaction is depressed. In other words, steel corrosion is initiated and accelerated in this location.

If i_c and i_a are stray current densities where the stray current flows into (at point B, cathodic area with the area of A_c) and flows out (at point C, anodic area with the area of A_a) at the reinforcement, the relationship between the overall stray current I_s and the anodic and cathodic currents can be expressed as follows:

$$I_s = i_c \cdot A_c = i_a \cdot A_a. \tag{9}$$

The passivity of steel in alkaline and chloride-free concrete also provides resistance to the stray current. Before the stray current is picked up by the reinforcement, a significant driving voltage (ΔU) has to be present between the point where the current enters the reinforcement (cathodic site, point B with surface area of A_c) and the point where the current returns to the concrete (anodic site, point C with surface area of A_a). ΔU equals the sum of the dissipative contributions due to the cathodic (ψ_c) and anodic (ψ_a) polarizations and the ohmic drop through the reinforcement (ψ_Ω). The driving voltage ΔU is thus dissipated by anodic and cathodic polarizations and by the ohmic drop within the rebar:

$$\Delta U = \psi_c + \psi_a + \psi_\Omega. \tag{10}$$

When the ohmic resistance is negligible (e.g. because of low resistivity of steel rebar), the sum of the anodic and cathodic polarizations equals the driving voltage ΔU between points B and C:

$$\Delta U = \psi_c + \psi_a. \tag{11}$$

The anodic and cathodic areas may not have the same size as has been assumed so far. The driving voltage ΔU may decrease when the cathodic area is significantly larger than the anodic area, such that the current density on the cathodic site is negligible compared to that of the anodic site; thus, $\psi_c \rightarrow 0$, so that $\Delta U \rightarrow \psi_a$. Therefore, under particular circumstances, ΔU may be relatively low; in other words, it will be easier stray current to be picked up by the reinforcement.

5.2 Conditions required for the reinforcement to pick up stray current

Considering ohmic drops due to resistance and polarization on both rail and reinforcement (when the stray current leaks out or flows into), the equivalent electrical circuit to this scenario is shown in Figure 15, which can be simulated by a series of two electrolytic cells I and II (see Figure 16).

The distance between points B and C is denoted L_{rebar} (m). $\varphi 2$ and $\varphi 3$ are potentials at points B and C on the reinforcement, respectively. For resistance per unit length (r_{rebar}, Ω/m) of rebar, there will be a potential drop between points B and C:

$$\varphi 2 - \varphi 3 = L_{rebar} \cdot r_{rebar} \cdot I_s. \tag{12}$$

Based on the mechanism of an electrolytic cell, the driving force for cell I (Figures 15 and 16) is ($\varphi 1 - \varphi 2$). To force the reactions to occur, the minimum electric potential (driving force) is the sum of the absolute potential value of the macro cell ($E'_{corr} - E_{corr}$), the polarizations in anodic and cathodic areas (ψ'_a and ψ'_c), and the ohmic drop ($\psi_{soil,1}$ and $\psi_{conc,1}$):

$$\varphi 1 - \varphi 2 = E'_{corr} - E_{corr} + \psi'_a + \psi_c + \psi_{soil,1} + \psi_{conc,1}. \tag{13}$$

For the electrolytic cell II, the same argument holds:

$$\varphi 3 - \varphi 4 = E_{corr} - E'_{corr} + \psi_a + \psi'_c + \psi_{soil,2} + \psi_{conc,2} \tag{14}$$

where, as aforementioned, E_{corr} and E'_{corr} are the equilibrium potential of reinforcing steel and rail, respectively, when the stray current is absent.

From Equations (10) and (12) to (14), the relationship of the factors can be given in the succeeding equations. That is, the condition required for the stray current to be

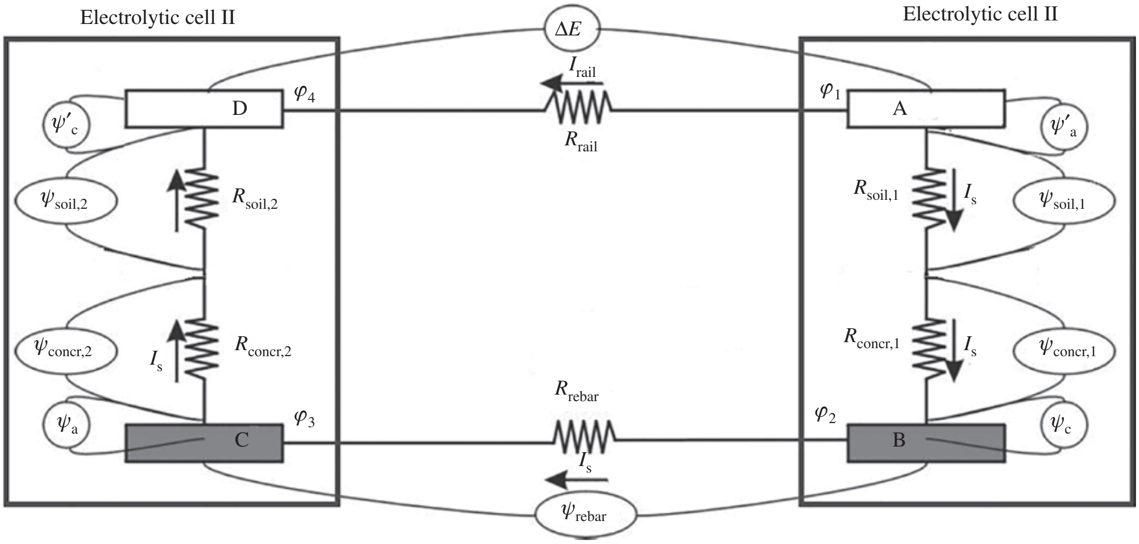


Figure 15: Schematic of stray current path considering the polarization and ohmic drop.

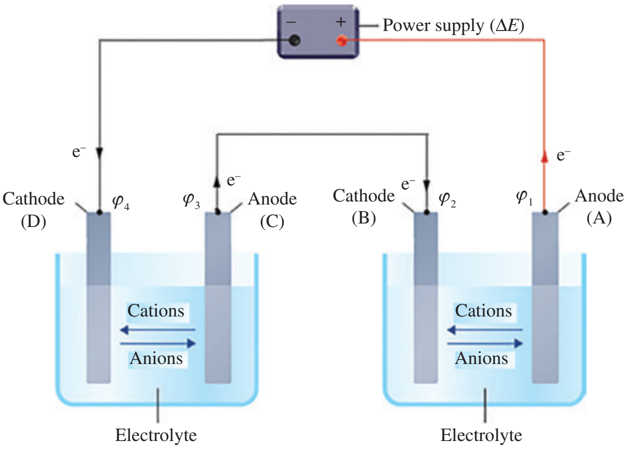


Figure 16: Series of electrolytic cells I and II.

picked up by the reinforcement in concrete near electrified traction system is

$$L_{rail}\cdot r_{rail}\cdot I_{return} = \psi_a+\psi_c+\psi'_a+\psi'_c+I_s\cdot R_{soil,1} \\ +I_s\cdot R_{conc,1}+I_s\cdot R_{soil,2}+I_s\cdot R_{conc,2}+I_s\cdot L_{rebar}\cdot r_{rebar}. \qquad (15)$$

Based on the definition of polarization, ψ_a, ψ_c, ψ'_a, and ψ'_c can be expressed as functions of the stray current (I_s) according to the polarization definition:

$$\psi_a = F_a(i_a) = F_a(I_s/A_a) \qquad (16)$$

$$\psi_c = F_c(i_c) = F_c(I_s/A_c) \qquad (17)$$

$$\psi'_a = F'_a(i'_a) = F'_a(I_s/A'_a) \qquad (18)$$

$$\psi'_c = F'_c(i'_c) = F'_c(I_s/A'_c). \qquad (19)$$

Then, Equation (15) can be also described as follows in Equation (20):

$$L_{rail}\cdot r_{rail}\cdot I_{rail} = F_a\left(\frac{I_s}{A_a}\right)+F_c\left(\frac{I_s}{A_c}\right)+F'_a\left(\frac{I_s}{A'_a}\right)+F'_c\left(\frac{I_s}{A'_c}\right) \\ +I_s\cdot R_{soil,1}+I_s\cdot R_{conc,1}+I_s\cdot R_{soil,2}+I_s\cdot R_{conc,2}+I_s\cdot L_{rebar}\cdot r_{rebar}. \qquad (20)$$

Based on the above analyses, it can be seen that when the electrochemical state of a system (including rail, reinforced concrete, and surrounding environment) satisfies the criterion expressed by Equation (20), the stray current will be picked up by the reinforcement in concrete near railways. Once this phenomenon takes place, corrosion will occur at locations where the stray current flows out from the reinforcement.

5.3 Impact factors for stray current-induced corrosion

A corrosion process in general is a function of related electrical/electrochemical and chemical/physical parameters (Faugt, 2006). A variation of these parameters can influence the corrosion process in many different ways. Due to this fact and the complexity in practical conditions, it may be very challenging to understand and then prevent the corrosion process completely. However, the better the understanding of the parameters involved is, the better the possibilities for mitigating corrosion.

Obviously, many factors related to the subentries of Equation (20) can affect the degree of risk for the stray current to be picked up by reinforcement. These impact factors can be classified into three categories: sources of stray current, ambient environments (soil, etc.), and interfered structure itself (reinforcement in concrete structures, for instance).

First of all, it is obvious that the measures for diminishing stray current disturbance to nearby constructions or variety of infrastructure should be provided at the initial stage of design. Constructions should be located as far as possible from stray currents sources – lines of electrified railway transport or high-voltage power lines for instance. Once the constructions are fixed and cannot be moved anymore, avoiding stray current sources or the reduction of the output (stray) current should be considered.

The resistivity of ambient environments (take the soil texture as an example) can influence the stray current direction and distribution significantly. Logically, there is a variety of factors affecting the resistivity of soil, which in turn affect the levels and distribution of stray currents: local depth, humidity (ground water level), chemical composition, and seasonal variation.

Figure 17 shows the soil resistivity measured at various test stations. Different results can be observed as depicted in Figure 17: (a) increased resistivity with increasing depth, probably indicating that the conducting ions are primarily present in the upper soil layers and drawn further down with rain; (b) decreasing resistivity with increasing depth found in totally wet peat bogs, where subsurface water movements may distribute ions and metabolites from biological activity; (c) different positions of the measurement points may have significantly different types and textures of soil, making the uncertainty more obvious with regard to judging the soil resistivity for a specific location; and (d) besides soil resistivity, as a global indicator, other factors (pH value, chemical composition, particle size of soil, etc.) may also affect stray current-induced corrosion of buried metallic structures; although these are not shown here, such factors should be also considered.

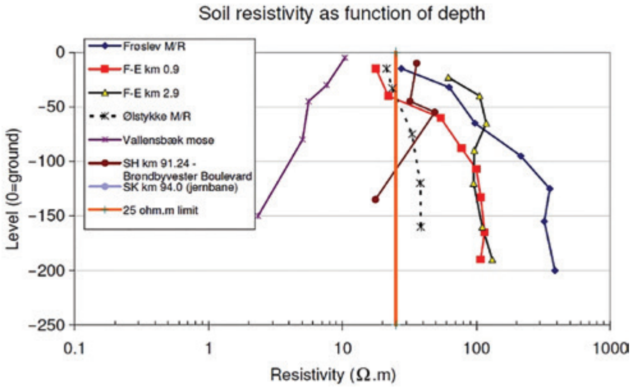


Figure 17: Soil resistivity measured as a function of depth-selected test locations (Faugt, 2006). Reprinted with permission from MetriCorr.

In terms of influencing stray current, the major contribution of soil resistivity is determining the path of any stray current that has already leaked from the traction system. In homogenous systems, high soil resistivity means that third-party buried structures are generally less vulnerable to corrosion damage, whereas, in low soil resistivity, the converse is true (Charalambous & Cotton, 2007). It is also found that at the locations where the current leaves a pipeline to soil interface, usually in the vicinity of low soil resistivity, stray current corrosion results (Bonds, 1997).

The details of the corrosion performance of a DC transit system with a floating return rail for a number of different soil resistivity structures and employing uniform, horizontal- and vertical-layer models were previously reported (Charalambous & Cotton, 2007). It was shown that a variation in the soil type along the route of a transit system (i.e. sudden change in soil resistivity along the path of a transit system) can lead to high local leakage-current densities affecting buried metallic structure, subsequently increasing their vulnerability to corrosion damage.

Stray currents may have more serious consequences in chloride-contaminated medium (e.g. concrete; Wang et al., 2011; Chen et al., 2012). Furthermore, the initiation of corrosion induced by stray current (viz. localized breakdown of the passive film can take place at anodic sites where the pitting potential is exceeded) is also favored in the presence of chloride.

Figure 18 plots the results of tests carried out in cement pastes with chloride contents up to 0.4% by mass

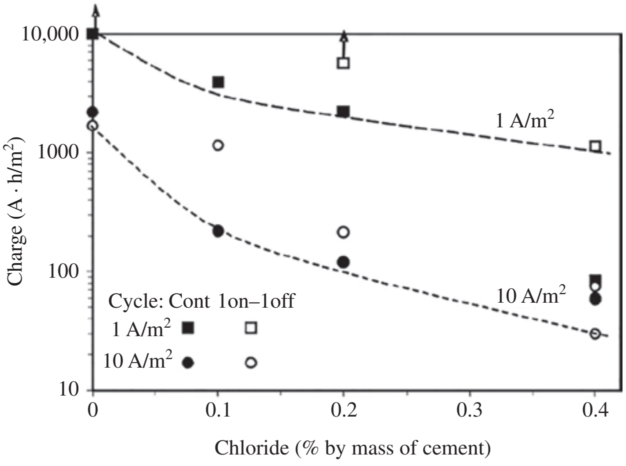


Figure 18: Charge required for the initiation of corrosion on steel plates, embedded in cement pastes with different chloride contents, which were polarized anodically with current densities of 1 or 10 A/m² (Bertolini et al., 2013). Reprinted with permission from Wiley-VCH Verlag GmbH & Co.

of cement. The charge (when supplying current) required for the onset of corrosion shows a remarkable decrease with the increase of chloride content. It also shows that lower current density levels (e.g. 1 A/m^2) can initiate corrosion in the presence of small amounts of 0.1% and 0.2% chloride by mass of cement.

Figure 18 also confirms the higher risks connected with higher anodic current densities: the charges required for corrosion initiation with a current density of 10 A/m^2 are more than one order of magnitude lower than those due to 1 A/m^2 (i.e. the times for initiation of corrosion are more than 100 times lower).

The protection that concrete cover offers to steel against stray current ceases when corrosion of the reinforcement has initiated, for example, due to chloride contamination or even the stray current itself. In this case, any current flowing through the steel will increase the corrosion rate at the anodic site, similarly as in buried steel structures.

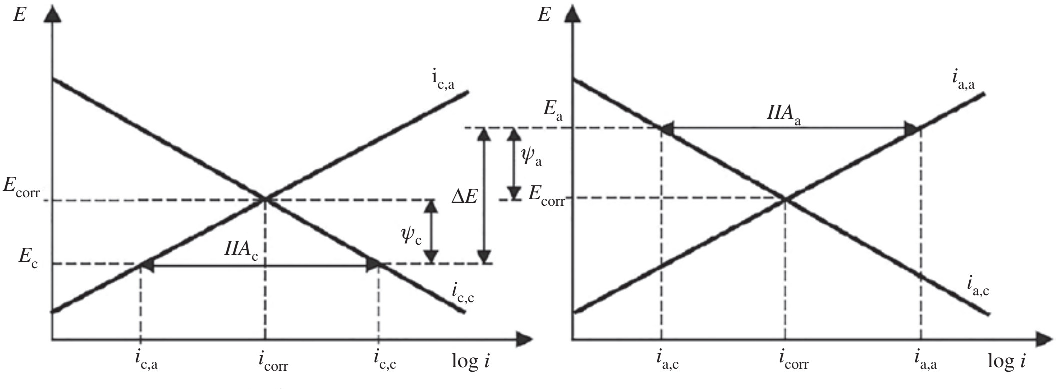
Figure 19 shows the cathodic and anodic responses of corroding reinforcement that is subject to stray current attack: for cathodic area (where the stray current enters the reinforcement), the anodic half-cell reaction is depressed (from i_{corr} to $i_{c,a}$) and the cathodic half-cell reaction is in domination (from i_{corr} to $i_{c,c}$) due to cathodic polarization (ψ_c).

In terms of the anodic area (where the stray current flows out from the reinforcement to concrete) of corroding steel rebar, even a small induced anodic polarization (ψ_a) can lead to an significant increase in the corrosion rate (corrosion rate from i_{corr} to $i_{a,a}$) as illustrated in Figure 19.

As discussed above, before stray current can be picked by the steel reinforcement, a driving voltage ($\Delta U = \psi_c + \psi_a$) has to be present. This voltage equals the sum of cathodic (ψ_c) and anodic (ψ_a) polarizations when the ohmic drop through the reinforcement (ψ_Ω) is negligible because of the low resistivity of the steel rebar.

Once the external environment is chloride-contaminated medium, the caused corroding steel surface is more susceptible to stray current attack: because under this particular circumstance, ΔU may be relatively low; in other words, it is easier to pick up stray current. Furthermore, it has been observed that if steel is subjected to pitting corrosion in chloride-contaminated concrete the anodic current increases the size of the attacked area (Bertolini et al., 2013).

The properties of an interfered structure itself plays a predominant role in picking up the surrounding stray current. In terms of reinforced concrete structure, the electrical resistivity of concrete has effects on the general corrosion process (such as corrosion caused by chloride or carbonation rather than stray current) of embedded reinforcement and the transfer of stray current. Concrete itself is well known for its ionic conductivity, whereas reinforcing steel is an electronic conductor (with the charge carriers being electrons) rather than an ionic conductor. The general process of reinforcement corrosion in concrete is partially controlled by the transport of ions through the concrete microstructure. Ions are charged and the ability of a material to withstand transfer of charge is dependent on the electrical resistivity. It is today widely accepted that the corrosion rate decreases with increasing concrete resistivity under common environmental exposure conditions (excluding submerged structures; Hornbostel et al., 2013). In a submerged structure, oxygen supply is limited; consequently, the cathodic reaction will be slow, although a sufficient amount of chloride is present.



Cathodic area

Anodic area

Figure 19: Schematic representation of electrochemical conditions in the cathodic and anodic zones of corroding reinforcement that is subject to stray current (Bertolini et al., 2013). Reprinted with permission from Wiley-VCH Verlag GmbH & Co.

A relationship between concrete resistivity and corrosion rate would allow the assessment of the corrosion state. The assessment criteria to quantify corrosion activity by concrete resistivity measurements can be found in the literature. However, a high variation between the threshold values is observed (Hornbostel et al., 2013). An upper limit of 1000 to 2000 Ωm can be identified from the comparison over which the corrosion rate will be low. As a lower limit, concrete with a resistivity under 50 Ωm is likely to allow heavy corrosion. On site, the resistivity values between 50 and 1000 Ωm are commonly obtained for concrete made of ordinary Portland cement (OPC), up to 6000 Ωm for blended cements (Polder et al., 2000).

Regarding stray current-induced corrosion, once stray current intrudes into reinforced concrete structure, due to the very low resistivity of reinforcing steel relative to concrete, a proportion of stray current will flow easily and preferentially into the reinforcement. To reduce stray current leakage from light rail systems, care must be taken to increase rail-to-earth isolation and to prevent inadvertent contact with the reinforcing steel used for the track support bed (Tinnea et al., 2007). To this aim, high-resistivity concrete rail bed was adopted combined with a dielectric rubber boot (Tinnea et al., 2017). A constructible high-resistivity concrete mix was developed using supplementary cementitious materials. The resistivity was 100 times greater than standard concrete. In addition, the concrete was highly workable and had a high early strength to minimize road closures.

6 Means for reducing stray current-induced corrosion: adopted standards and criteria

In terms of judging the risk of stray current-induced corrosion, a variety of standards exist with regard to different situations. The application of Faraday's law requires the consideration of current flows, whereas the most common site of validation measurement are potentials in structures and utility assets to a local reference. According to the Chinese National Standard GB/T 19285-2014 "Inspection of corrosion protection for buried steel pipelines", when the positive shift of pipe-to-soil potential is higher than 20 mV or the potential gradient of soil is higher than 0.5 mV/m, direct stray current corrosion should be considered to be existent. When the positive shift of the pipe-to-soil potential is higher than 100 mV or the potential gradient of soil is higher than 2.5 mV/m, electrical drainage or other protective measures must be present. Measurements should be lasting at least 30 min and the average value should be used where the potentials are rapidly fluctuating. For buried pipeline, sacrificial anode should be disconnected at least 24 h before the test to eliminate the influence of current from the CP system. The British Standard BS EN50162-2004 "Protection against corrosion by stray current from direct current systems" recommends a similar judgment method, giving the acceptable positive potential shifts for buried metallic structures without CP, considering the influence of IR drop.

The IEC 62128-2 "Railway applications-fixed installations-electrical safety, earthing and the return circuit – Part 2: Provisions against the effects of stray currents caused by d.c. traction systems" applies criteria based on the exceedance of absolute or averaged corrosion potential thresholds without regard to current flows. The IEC 62128-2 applies voltage limits in two ways: (1) longitudinal voltage drop in tunnel reinforcement (0.1 V of limitation) and (2) structure to the earth potential shifts in tunnel reinforcement (maximum 0.2 V).

In particular, the requirements for protective provisions against the effects of stray currents were also specified in SP0169-2013 (formerly RP0169) "Control of external corrosion on underground or submerged metallic piping systems". This applies to all metallic fixed installations, which form part of the traction system, and also to any other metallic components located in any position in the earth, which can carry stray currents, resulting from the operation of the railway system. To this end, the EN 50162-2004 completes IEC 62128-2 and SP0169-2013 by establishing the general principles to be adopted for minimizing the effects of DC stray current corrosion on buried or immersed metal structures.

To meet standard requirements as shown above, the measures should be taken to reduce stray current corrosion risk. This aim can be achieved by modifying the impact factors of stray current-induced corrosion. As for the order of importance of these factors, as mentioned by EN 50162:2004 back in 2005, the "measures taken to minimize the effects of stray current interference should commence with the source of the stray current interference".

If measures taken to handle the effect of stray current sources are impractical or ineffective, the attention should be focused on the external environment and the interfered structure itself. In some particular cases, actions should be taken on both to achieve an acceptable interference level of stray current. Consequently, specific measures can be adopted to limit the stray current interference from the metallic structure and these can be based on three different approaches (Bertolini et al., 2013): (1) prevent the stray current from developing at the source, (2) prevent the stray current from reaching the structure, and (3) design the structure in such a way that the harmful effects are reduced.

With regard to the above considerations, a further discussion on the protective measures for reducing the risk of stray current corrosion will be performed, considering the above theoretical analysis and several impact factors on stray current corrosion risk.

6.1 Stray current sources

Additionally, the means for reducing stray current corrosion should also be tailored according to which source the stray current comes from. As the most frequent stray current source, the electric power traction system will be taken as the example in the following part to describe what measures can be taken in such cases.

The essential elements of a transit system are the rails, power supply, and vehicles. The design and placement of all these dictate the stray current effects in terms of the total stray current leaving the rails. With regard to the modes of a running vehicle, including accelerating, coasting, constant speed, or braking, the results of field tests and numerical simulations (Xu et al., 2013) show that the rail potential in the acceleration and brake modes is significantly higher than that in the other modes.

Level crossings are highly susceptible to stray current effects: because of safety concerns, it is inevitable that vehicles need to brake and accelerate at level crossings, which means that the servo current is higher than normal situations. Subsequently, the density of the return current in the rail and leaked-out current (stray current) is higher. Due to poor rail insulated boots, switch machines, and the accumulation of brake dust near level crossing or passenger platforms (Willson, 2006; Zan et al., 2014), once the current leaks out from the rail, corrosion can occur more easily at the rail foot and then induce stray current corrosion when the leaked-out current flows into nearby metallic structures.

Consequently, rail base corrosion, which is commonly found in level crossings, can represent a dangerous condition for the level crossing itself but also for the track integrity and eventually for the safety of transit systems. In addition to subsequent stray current corrosion, combined road/railroad loadings, inconvenience for repair, high cost, and disturbance of traffic and railroad operations at level crossings, it is clearly necessary to inspect and intervene in these locations on a more frequent basis (Rose, 2013).

As aforementioned, owing to the longitudinal resistance of rails and their imperfect insulation to ground, part of the return current leaks out from the running rails and flows along parallel circuits, before returning onto the rail and the negative terminal of the substation, forming the stray current. Apparently, the higher the contact resistance between the rails and the ground (insulation) and the less the longitudinal resistance of the rail are, the lower are the leakage currents from the railway into the ground.

The reduction of the longitudinal resistance can be attained by the connection of adjacent joints using flexible copper wire or other conductors. According to existing standards, in the case of increasing the contact resistance between the rails and ground, rails should be bedded in broken stone, gravel, or other equivalent (regarding their insulating properties) ballast. Wooden ties must be impregnated with nonconductive oil antiseptics, whereas at the time of application of ties of reinforced concrete it is necessary to insulate them from the rails (Riskin, 2008).

Another manner to reduce stray current levels below a damage-causing value may be increased power system cross-bonding (Tzeng & Lee, 2009). Reducing the distances between traction substations is another measure that can be taken for controlling stray current. However, this solution increases the construction cost, so the optimum placement of traction substations should be carried out based on peak service conditions (Alamuti et al., 2012).

6.2 Stray current collection system

If the total stray current for a given system design is high, a considerable corrosion of the supporting infrastructure and of a third-party infrastructure may occur. In this situation, a stray current collection system (current collection mat or cable) may be needed to control the path through which the stray current returns to the substation.

As shown in Figure 20, a stray current collection system can be constructed under the rails to “capture” the stray current and avoid damage to the segments. Such collection systems usually take the form of reinforcement in the concrete track bed of a traction system. This reinforcement is bonded along its length to provide a continuous and relatively low resistance path. The stray current leaking from the running rails is intended to flow into this collection system and be captured upon it, as opposed to flowing through the surrounding construction or other local conductors such as utility pipes/cables.

The performance of a stray current collection system is highly dependent on the conductivity of the system

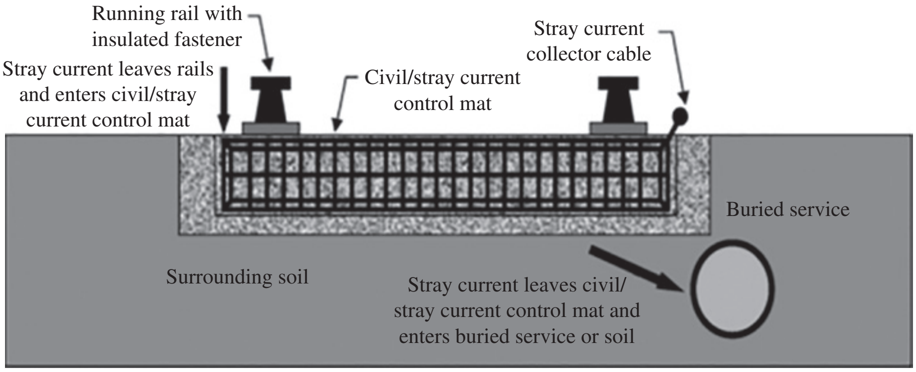


Figure 20: Stray current collection system under the rail (Cotton et al., 2005). Reprinted with permission from IEEE.

itself and of the neighboring soil. Extremely high efficiencies can be achieved when the material surrounding the stray current collection system is highly resistive (Niasati & Gholami, 2008). The arrangement of a reinforcement mat, being bonded electrically back to the substation through parallel conductors, has therefore a dual function: (1) to prevent the corrosion of the reinforcement bars themselves and (2) to act as a secondary level of protection against stray currents penetrating the surrounding earth and possibly into buried services (Niasati & Gholami, 2008).

6.3 Railway earthing systems

The railway earthing system has an important role on the magnitude of stray currents. Schemes adopted in the earthing of a railway system include solid (direct) earthed, floating (unearthed), and diode earthed (Paul, 2002; Lee & Lu, 2006; Tzeng & Lee, 2010). Based on the analysis of the grounding strategies, it was found that various earthing schemes can change the stray current quantity to a different extent (Cotton et al., 2005; Tzeng & Lee, 2009; Alamuti et al., 2012).

Simulation results clearly indicate that the stray currents and rail potentials are closely related in both unearthed and earthed systems. Generally, the rail potential of the rail in the unearthed system is higher, but it would reduce considerably when the substations are earthed. However, it was shown that the stray current increases where the direct earthing of rails is implemented (Alamuti et al., 2012).

Diode-grounded schemes represent a compromise between ungrounded and direct-grounded schemes. They are often used to eliminate the problems of stray current-induced corrosion from a direct-grounded system. However, practical and theoretical studies have shown that diode earth strategies may result in high touch potentials and stray currents at the same time. As a result, among the three available approaches, the ungrounded scheme (floating) is the most effective in view of the levels of stray currents and rail potential.

6.4 Electrical drainage bond

As aforementioned, corrosion only occurs when the stray current leaves the structure; it does not occur at the section where the current enters the structure or when it leaves the structure to another metallic structure other than to enter the soil or concrete (i.e. electrolyte). To mitigate the corrosion effects of stray current, a drainage bond can be used (Figure 21). Therefore, by diverting most of the current into the bond rather than into the soil, the amount of corrosion of the metal structure will be reduced. A drainage bond (Figure 21) is a metallic joint between the structure and rail that provides an alternative path for the stray current to return to the rail (Niasati & Gholami, 2008).

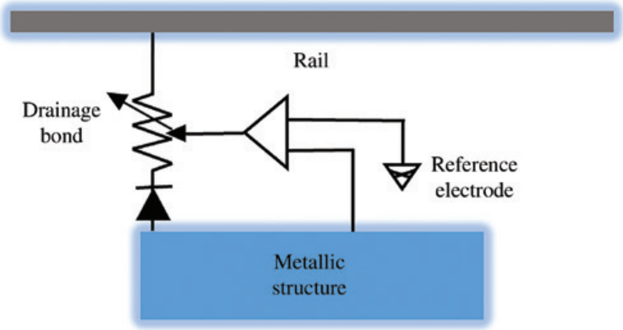


Figure 21: Schematic of drainage bond for mitigating the corrosion effects of stray current (Niasati & Gholami, 2008). Reprinted with permission from IEEE.

In practice, for complex systems, the design of bonds is not a simple matter. The drainage bond connection to the underground structure should be located where the railway and the structure cross or where they are closest together.

In addition, the location should be convenient for checking the equipment and where it does not interfere with traffic (Niasati & Gholami, 2008). Stray currents sometimes tend to be dynamic in nature, with the direction of the current reversing from time to time. In such cases, simple bonding is insufficient, and additional installation of diodes will be required to protect a critical structure at all times (Revie, 2008; Roberge, 2012).

Until the recent years, it was considered sufficient to rely on the traditional tie-wires used to assemble a reinforcement mesh to provide bonding. However, as a result of some failures in practice, this view no longer holds for structures associated with DC traction systems. Where weldable steelworks are used, spot welding may provide the best solution, although the effect of this on the structural properties of the systems needs careful evaluation (Vernon, 1986).

6.5 Electrical shield

Where a metallic structure passes through the influence area of a surrounding stray current source, it is possible to reduce the amount of picked-up stray current using electrical shields. In cathodic shielding, the aim is to minimize the amount of stray current reaching the structure at risk. A metallic barrier (or “shield”) that is polarized cathodically is positioned in the path of the stray current as shown in Figure 22. The shield represents a low-resistance preferred path for the stray current, thereby minimizing the flow of stray current onto the interfered structure.

The effects of location and the manner of installing a metallic shield on mitigating the effects of stray current were studied experimentally by Du et al. (2015). The metallic shield was connected with the cathode of the interference source and the picked-up stray current value was monitored. Additionally, two kinds of cathodic shielding phenomena of the sacrificial anode CP systems, which are caused by a metal barrier, were investigated by numerical simulations and experiments (Liu et al., 2013).

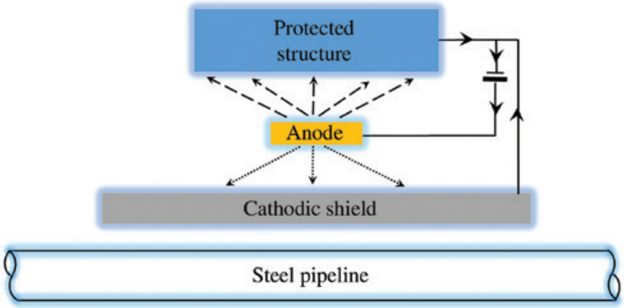


Figure 22: Schematic of a cathodic shield to minimize anodic interference.

If the shield is connected to the negative terminal of the power supply of the interfering structure, its effects on the protection levels of the interfering structure have to be considered; these will obviously be reduced for a given rectifier output (Roberge, 2012).

Although the shields can reduce the stray current pickup, interference current still can be expected to flow away from the pickup area to remote discharge points at which the interfered metallic structure will be corroded. This current flow needs to be reversed. This may be done with galvanic anodes or bonds if the shields have reduced stray current pickup to a reasonably small magnitude (Peabody, 2001).

6.6 Insulating couplings

By installing one or more insulating couplings, the pipeline becomes a less favorable path for stray currents. Such couplings are often useful for minimizing stray current damage. However, they are less useful if voltages are so large that current is induced to flow around the insulating joint, causing corrosion near the couplings as shown in Figure 23 (Revie, 2008).

6.7 Intentional anodes and CP

Sacrificial anodes can be installed at the current discharge areas of interfered structures to mitigate stray current corrosion, stray currents then cause corrosion only on the intentional anode, which is easily replaced at low cost. This mitigation method is used frequently in pipelines disturbed by stray current and is most applicable to relatively low levels of stray currents (Roberge, 2012).

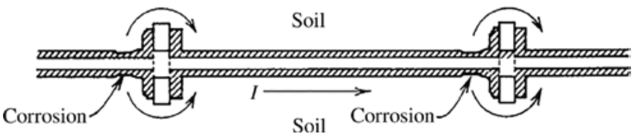


Figure 23: Effect of current flowing along a buried pipeline on corrosion near insulated couplings (Revie, 2008).
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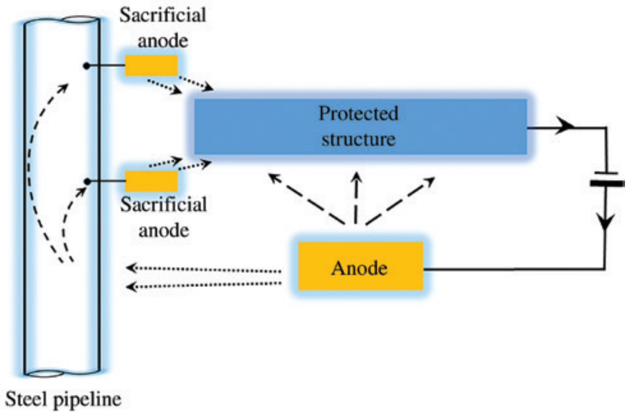

Figure 24: Schematic of sacrificial anodes to mitigate cathodic interference.

As shown in Figure 24, the current is discharged from these anodes rather than from the structure at risk. The importance of placing the anodes close to the interfering structure is obvious: to minimize the resistance to current flowing from the anodes. The less noble anodes will generate a CP current, thereby compensating for small amounts of residual stray currents that continue to be discharged from the interfered structure.

CP is installed whenever the intentional anode is not sufficient to overcome all corrosion caused by stray currents (Revie, 2008). The materials applied for manufacturing grounding anodes in CP by an impressed current are characterized by their wide variety. Steel anode dissolution at current outputs is close to 100%. Consequently, steel grounding anodes, designed for a long-term service life, should have a maximal weight (Riskin, 2008).

6.8 Application of coatings

The most important component of the protection system for underground structures is their insulation from ground. The higher the construction-ground resistance is (i.e. the better the quality of the insulating coating of the construction is), the smaller the stray current magnitudes penetrating to the construction.

The application of waterproof coatings to buried reinforced concrete structures may reduce the stray current flowing through the concrete (Bertolini et al., 2013). In electrochemical plants, to prevent stray current from flowing into the reinforced concrete structures, standards forbid the application in electrochemical plants of materials that are capable of absorbing moisture (concrete, nonglazed porcelain, ceramics, etc.) without special treatment by water-repellent and insulating compositions (Riskin, 2008).

It must be noted that the use of protective coatings to reduce stray current damage should be implemented before the installation of buried structures. It is usually impractical to apply such coatings after the installation. Besides, the use of coatings to mitigate the influence of stray currents should only be considered at the current pickup areas. It is not recommended to rely on additional coatings at current discharge areas, because rapid and localized corrosive substance penetration is to be expected at any coating defect. In general, if a macroscopic anode and cathode exists on a structure, coatings should never be applied to the anode alone in view of corrosion protection (Roberge, 2012).

6.9 Electrical discontinuity

In practical applications, it is impossible to completely exclude defects in coatings applied on large structures. Therefore, alongside the application of insulating coatings, the longitudinal resistance of pipelines can be increased to decrease the magnitude of stray currents as well as to minimize the effect of defects. For this purpose, the electric sectionalization of pipelines is executed. This consists of the application of insulating flanges and the insertion of insulating material into the pipelines. In this way, it is possible to significantly lower the magnitude of stray current on the pipeline.

However, along with a decrease of the stray current density, the number of anodic zones, where the current is draining off from the pipeline into the ground, increases. This number is equal to the number of sections “breaking” the current flow along the pipeline. Therefore, sectionalization is usually carried out together with the application of grounded current taps (Riskin, 2008).

Other than pipeline networks, the reduction of stray currents for various structures can be also achieved by sectionalization (e.g. for maintenance platforms of electrolyzers or underground reinforced concrete structures). For instance, overlaps of the installation for electrolyzers should be separated by insulation seams from adjoining walls, columns, and other elements of the building.

7 Monitoring and evaluation of stray current-induced corrosion risk

Although stray current leakage can be controlled by some measures as mentioned above, its existence is inevitable in some special scenarios. In cases where there is a possible corrosion risk due to stray DC interference, the analysis of the situation shall consider electrical properties and the location of the possible source of interference as well as recorded anomalies. As reported (Briglia et al., 1999; Zakowski & Sokólski, 1999; Darowicki & Zakowski, 2004; Kerimov et al., 2006; Zakowski, 2009; Ogunsola et al., 2012; Lelák & Váry, 2013), there are four principal ways to identify stray current interference on pipelines: (1) structure to electrolyte potential fluctuations, (2) deviations from normal structure to electrolyte potentials, (3) voltage gradients in the electrolyte, and (4) line currents in pipeline coupons or metallic cable sheaths.

The assessment of corrosion attack by stray currents of bars in reinforced concrete structures is even more problematic. In addition to the above-mentioned factors, a number of new ones are added. Among these are the following: the ramification of bars inside the concrete, the impossibility of breaking off the reinforcement (which form closed circuits of metallic conductors inside the concrete) to measure stray current values, and the dependence of current distribution on the humidity of the concrete at different sites of the structure. Additionally, in the case of prestressed concrete structures, the expected cathodic areas should also be monitored to investigate the risk of hydrogen embrittlement.

The monitoring of stray current in reinforced concrete may be carried out by embedding permanent reference electrodes at positions identified as critical to track the presence of stray currents, to determine the direction of flow, and to locate anodic and cathodic areas. For example, a stray current sensor with a cylindrical twisted fiber was proposed (Xu et al., 2014a) to monitor the presence of stray current. The authors demonstrated a quantitative method of linear birefringence on the sensing fiber, and a configuration for the stray current sensor was suggested. The reported setup also included a broadband light source, a polarizer, a coupler, a sensing head, a mirror, a polarization controller, a polarization beam splitter (PBS), and a high-speed optical power meter.

Other measures that can help in detecting the presence of stray current in reinforced concrete are based on the potential difference present between different parts of the structure due to the ohmic drop produced by the stray current.

However, in some cases, it is impossible to measure the stray current on site, so some other methods [e.g. backpropagation (BP) neural network predictive model, novel or numerical predictive model, software tool, etc.] for stray currents calculation have been proposed based on various considerations and mechanisms (Ardizzon et al., 2003; Lowes, 2009; Cao et al., 2010; Dolara et al., 2012; Charalambous et al., 2013a, b; Fichera et al., 2013; Li & Kim, 2013; Xu et al., 2014b) for specific objects of buried metallic pipeline or reinforcement in reinforced concrete. Methods based on unequivocal and precise hazard criteria have been also suggested in view of the evaluation or prediction for the corrosion degree of metallic materials caused by stray current (Zakowski & Darowicki, 2000). Due to the generally limited number of reference electrodes, it is also necessary to predict the corrosion status of the metal materials in an area without reference electrodes. In this regard, Wang et al. (2013) approximated the nonlinear mapping between characterization parameters and influential parameters using a radial basis function (RBF) neural network.

A nondeterministic approach was introduced to study the stray current effects generated by DC railway or tramway lines on buried pipelines by Lucca (2015). The potential shift induced (via conductive coupling) on the pipelines by the stray current dispersed in the soil is evaluated by means of a suitable equivalent circuit combined with a Monte Carlo procedure. OKAPPI, a numerical model for calculating CP problems involving underground pipelines, was extended to situations involving stray currents (Brichau et al., 1996).

Machczynski et al. (2016) presented the electric circuit approach based on the earth return circuit theory to model stray current interference on extended structures. In the approximate method, the equivalent rail with current energization is simulated as a large multinode electrical equivalent circuit with lumped parameters. The circuit is a chain of basic circuits, which are equivalents of homogenous sections of the rail. The electrode kinetics (polarization phenomenon) was taken into account in the model.

Some mathematical models based on different methods [finite element method (FEM), boundary element method (BEM), etc.] were established to assess the stray current corrosion phenomena of ductile iron pipe (DIP) located in the vicinity of cathodically protected steel pipe (Li & Kim, 2013), to model the corrosion of the unprotected structures due to a stray current, resulting from a nearby CP system (Kim et al., 1999), and to simulate stray current interference of underground steel structures through a traction power systems (Peelen, 2007).

A model of an electric train with a traction power substation, running rail, and third rail was simulated in MATLAB/Simulink (Zaboli et al., 2017). In the simulated FEM model, the amounts of stray currents in different soil types, with and without collection mats, were compared. Other researchers (Ogunsola et al., 2012) proposed an integrated model for the assessment of stray current for a DC-electrified railway in which the factors such as the train characteristics, timetabling, headway, and multiple train movement were considered. An analysis of the stray current magnitude under worst-case train operating conditions (i.e. multiple trains with a 90 s headway accelerating) and highlight factors that determine the efficiency of the stray current collection system was provided.

A unified chain model of a DC traction power system was also proposed to simulate the distribution of rail potential and stray current (Du et al., 2016). Field tests and simulations were carried out to study whether over-zone feeding has an impact on rail potential and stray current. The results show that over-zone feeding widely exists in a DC traction power system and that the rail potential and stray current can be reduced effectively by preventing the over-zone feeding of traction current.

In addition, the numerical simulation program BEASY was used to study the corrosion effect of DC stray current that an auxiliary anode bed generated in an impressed current CP system (Cui et al., 2016). The effects of crossing angle, crossing distance, distance of the two pipelines, anode output current, depth, and soil resistivity were investigated. The results indicate that pipeline crossing substantially affects the corrosion potential of both protected and unprotected pipelines. Pipeline crossing angles, crossing distances, and anode depths have no significant influence. Decreasing anode output current or soil resistivity reduces pipeline corrosion gradually. A reduction of corrosion also occurs when the distance between two parallel pipelines increases. Besides, BEASY was also chosen to study the effect of interference of adjacent pipeline corrosion caused by DC stray current (Cui et al., 2015). In this case, the BEM was adapted to establish a model containing four pipelines.

Based on many existing models, the Company Movares (The Netherlands) has developed the new simulation tool STARTRACK (stray current analysis tool for railway tracks; Smulders & Janssen, 2006). Based on the physical properties of soil, a set of equations were derived to determine the values of discrete components in the model, such as the resistance between the track and structural works. The earth was modeled with two layers, therefore providing the possibility to take the properties of the top earth layer into account.

ElSyCa N.V. (Belgium) proposed a simulation software for the CP of underground pipeline networks (Bortels, 2002; Bortels et al., 2010; Baeté et al., 2015). This software uses an advanced model for the coating quality, taking into account the local soil resistivity, holiday ratio, average holiday size, coating thickness, and resistance. The model is solved using a combination of the BEM for the external problem (the soil) and the FEM for the internal problem (the metallic conductor of the pipe; Bortels, 2002). Special "pipe elements" have been used to reduce the calculation time. All standard kinds of CP interferences can be dealt with as well as stray currents coming from other CP installations, DC traction systems, HVDC transmission lines, earthing systems, etc. As a result, the model gives the pipe-to-soil potentials along a pipe, the axial currents flowing through the pipes, as well as the radial current densities leaving or entering the pipe walls. Besides, the model allowed performing sensitivity analysis, identifying the high-risk zones (Baeté et al., 2015).

In addition, it is known that stray current is an unstable physical quantity, that is, its direction and amplitude are uncertain underground. Thus, it may be necessary to analyze the influence area of the stray current, which can provide suggestions for the placement of buried metallic pipelines.

For instance, the point of maximum exposure of a tram or train line can be pinpointed by correlating the pipe potential with the voltage between the pipeline and the tram/train rails (Zakowski & Darowicki, 2000; Peabody, 2001). Correlations were made at a series of locations through the exposure area. At each location, the slope of the X–Y correlation spectrum is calculated. The slope is a measure of exposure to stray current: the greater the slope is, the greater the exposure (Zakowski & Darowicki, 2000; Peabody, 2001). However, the interpretation of the results is sometimes still ambiguous, especially when the correlation data potential-voltage will not fall along a straight line. Such a case may occur when several stray current sources affect the pipeline (Zakowski & Darowicki, 2000).

The electric field in the ground connected with the flow of stray currents in an electrolytic environment is not identical in time or in space. The changes of this field are random in character. Ferenc (1992) estimated the current and direction of the electric field in the ground (hence the flow direction of stray currents in the ground) based on potential difference measurements between pairs of electrodes placed on the ground surface perpendicularly to each other.

8 Concluding remarks

Stray current arising from different power sources and then circulating in metal structures may initiate corrosion or even accelerate existing corrosion processes. Nevertheless, stray current-induced corrosion is still not sufficiently recognized in practice despite the far-reaching range and scale of dangerous or unwanted interactions of stray currents under favorable conditions and environment.

The aim of this review was to outline and bring together main aspects with regard to stray current-induced corrosion, namely, the sources of stray current, characteristics and mechanism of stray current corrosion in view of electrochemical aspects, methods and techniques for evaluation, and monitoring and control of stray current-induced corrosion for steel in infrastructure. Based on the reviewed literature, some concluding remarks can be drawn as follows.

Stray current can easily and unexpectedly arise from electrified traction system, making stray current-induced corrosion one of the most severe forms of damage to buried structures, such as tunnels and underground pipelines, located nearby the driving power sources. Irrespective of the origin of stray current, it is easily “picked up” by metallic conductive paths and later on discharged in the surrounding soil or water, causing stray current-induced corrosion or the acceleration of existing corrosion on these metallic structures.

Although stray AC is much “safer” than stray DC flow, AC can also affect the anodic behavior of steel. The relationship between AC density, frequency, and corrosion rate has been studied and reported. However, the coexistence of both AC and DC stray currents has not been considered so far. Attention should be further paid on the possible synergistic effects of AC and DC stray currents that might, under specific circumstances, be able to stimulate the corrosion rate of depassivated steel or to promote corrosion on passive steel.

To deduce the conditions required for a steel reinforcement to pick up stray DCs, a theoretical analysis was proposed in Section 5.2, involving factors that can affect the risk and subsequently the level of stray DC-induced corrosion. The various parameters involved in this analysis, such as the sources of stray current, ambient environments (soil, concrete, etc.), and types of interfered structure (reinforcement in concrete structures, or buried pipelines for instance), together with the corresponding protective measures for reducing the stray current corrosion risks, were presented in detail in Sections 5.3 and 6. Furthermore, in terms of the procedures for practical evaluation and accurate prediction of stray current-induced corrosion, specific indicators such as structure to electrolyte potential, deviations from normal structure to electrolyte potentials, voltage gradients in the electrolyte, and line currents in metallic structures were summarized and evaluated, pointing out their importance for stray current-induced assessment and/or risk analysis.

Intuitively, assessments of stray current corrosion impacts can be made as qualitative assessments using a mix of engineering judgment and applications of Faraday’s law to assess the cumulative mass of metal loss over the target operating period. However, the application of Faraday’s law requires consideration of current flows, whereas the most common site of validation measurement are corrosion potentials in railway system structures and utility assets to a local reference. The ohmic drop (IR component) contributes by resistance between the working electrode and the reference electrode and can be always involved during potential shift measurement in practice, especially in reinforcing concrete due to the relatively higher resistivity of the concrete matrix surrounding the steel rebar. This kind of undesired signal (burdening of measurement results with the IR component) leads to uncertainties, even overestimations on stray current corrosion evaluation. In these situations, IR drop should be considered and handled carefully.

The use of models for predicting actual stray current levels remains limited. The main reason is a practical one: normally in real-life practice, it is very difficult to determine the local properties of the most critical parameters, such as soil resistivity and rail-to-earth resistance. At the present stage, these parameters are assumed to be homogenous and average values are adopted. Local deviations from this homogenous model can cause relatively large deviations in the results. Therefore, efforts should be taken to improve the accuracy and reliability of models.

Overall, it can be concluded that despite the various reports on the subject of stray current-induced corrosion a more comprehensive approach is necessary to thoroughly evaluate the process. For example, if reinforced concrete structures are considered, a parallel systematic evaluation of electrochemical phenomena (steel reinforcement) together with micromechanical properties (concrete matrix and interfaces) will allow a more accurate appraisal of stray current-induced risks and their consequence. This will also bring clarity for optimizing the existing approaches to predict and control stray current-induced corrosion in practice.

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