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Corrosion and stray currents at urban track infrastructure

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Subject review

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Rails are a part of track structure where corrosion process inevitably occurs, except if they are fully insulated and devoid of contact with any other part of the structure (sleepers, fastening accessories) or electrolyte like moist soil or water in track structure. Corrosion occurs much faster in the presence of stray currents, which very soon results in the loss of material at the rail foot. The paper presents an overview and description of parameters influencing stray current levels, such as electrical potential in rail and longitudinal rail conductivity, rail-to-earth electrical resistance, electrical conductivity of load-bearing concrete layers of truck structure, and electrical conductivity of soil.

Key words:
rails, corrosion, stray currents, rail potential, rail-to-earth electrical resistance

Pregledni rad

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Korozija i lutajuće struje na tračničkoj infrastrukturi u urbanoj sredini

Tračnice su dio kolosiječne konstrukcije na kojima će se korozija neizbježno pojaviti, osim ako su u potpunosti izolirane te nemaju kontakt s bilo kojim drugim dijelom kolosijeka (prag, pričvrsni pribor) ili elektrolitom poput vlažnog tla ili vode u kolosiječnoj konstrukciji. Korozija će biti znatno brža u prisutnosti lutajućih struja, što će kroz vrlo kratko vrijeme rezultirati gubitkom materijala na nožici tračnice. U radu je dan pregled i opis parametara koji utječu na razinu lutajućih struja, poput električnog potencijala u tračnici i uzdužne provodljivosti tračnice, električnog otpora između tračnice i tla, kao i električne provodljivosti nosivih betonskih slojeva kolosiječne konstrukcije i električne provodljivosti tla.

Ključne riječi:
tračnice, korozija, lutajuće struje, električni potencijal tračnice, električni otpor između tračnice i tla

Übersichtsarbeit

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Korrosion und Streuströmungen auf der Schieneninfrastruktur in der städtischen Umgebung

Schienen sind ein Teil der Gleisstruktur, auf welcher unweigerlich Korrosion auftritt, ausgenommen, sie sind vollständig isoliert und haben keinen Kontakt mit irgendeinem anderen Teil des Gleises (Schwelle, Befestigungszubehör) oder Elektrolyten des feuchten Bodens oder Wasser in der Gleiskonstruktion. Die Korrosion wird bei Vorhandensein von Streuströmungen viel schneller sein, was in kürzester Zeit zu Materialverlust am Schienenbein führen wird. In der Abhandlung ist eine Übersicht und die Beschreibung der Parameter darlegt, welche sich auf das Niveau der Streuströmungen auswirken, wie auf das elektrische Potenzial der Schiene und die Längsleitfähigkeit der Schiene, den elektrischen Widerstand zwischen der Schiene und dem Boden, wie auch auf die elektrische Leitfähigkeit der tragenden Betonschichten der Gleichkonstruktion und die elektrische Leitfähigkeit des Bodens.

Schlüsselwörter:
Schienen, Korrosion, Streuströmung, elektrisches Schienenpotenzial, elektrischer Widerstand zwischen Schiene und Boden

1. Introduction

Tram systems and light urban railway systems are the main form of transport in urban areas of many European metropolitan centres. They are realized within the roadway or form a separate right-of-way, and their structures may vary to a great extent. When considering corrosion processes that affect rails, it must be noted that the most important characteristic of the track is the way in which rails are insulated, which in turn depends on the way in which rails are fastened to their support. In the case of continuous fastening, rails are placed into grooves realized in the load-bearing concrete support and, after the track is positioned along the length and height, the free space is filled with an elastic material. In order to save on material used, PVC pipes are very often used for this purpose (Figure 1) [1]. In these tracks, rails are fully separated from the surrounding structure by elastic material, and are hence protected against corrosion processes.

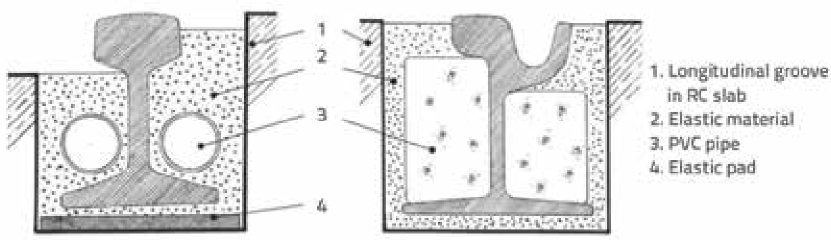

Figure 1. Example of continuously insulated rails in an embedded track [2]

In the case of individual supports, rails are fastened onto the support via fastening systems. These are mostly track systems without individual sleepers where concrete support layers are used, and rail fastening positions are integrated into the load bearing layer [1, 3]. Tram infrastructure realised in Zagreb is an example of such structures where the rail leans via a neoprene setting pad onto the steel support plate and the synthetic composite bearing at every one-meter intervals [4]. One of the first fastening systems applied on tram infrastructure in Zagreb was the single elastic fastening system ZG 3/2 (Figure 2a). However, due to deficiencies of this system, other systems have been introduced in the meantime and the system that has most frequently been used over the past twenty years is the enhanced-elasticity fastening accessory (the PPE system) and the double elastic fastening accessory (the DEPP system) [5]. Unlike the ZG 3/2 system, PPE and DEPP systems feature a ribbed neoprene pad under the steel support plate. This pad provides for better elasticity and insulation of the fastening accessory (Figures 2.b and 2.c) which will be shown further on in this paper as an advantage with regard to the influence of stray currents. The basic difference between the DEPP and PPE systems is in separation of the anchoring screw from the elastic clip and in greater thickness of the ribbed neoprene pad in case of the DEPP system [6, 7].

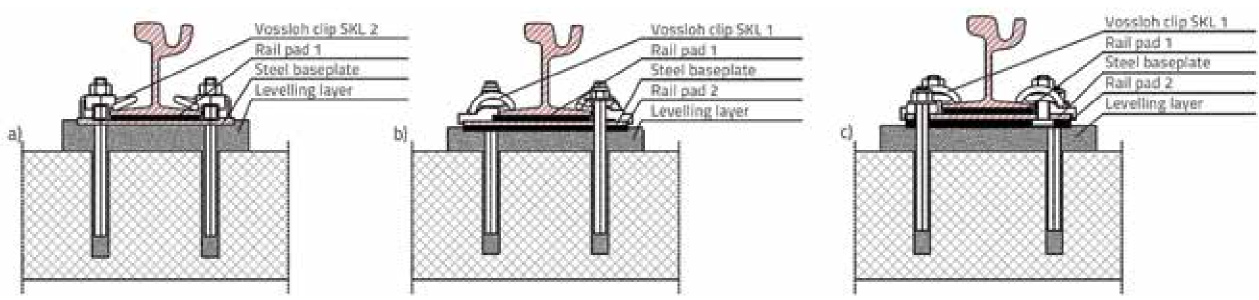

Figure 2. Cross section of fastening systems ZG 3/2, PPE, DEPP [8]

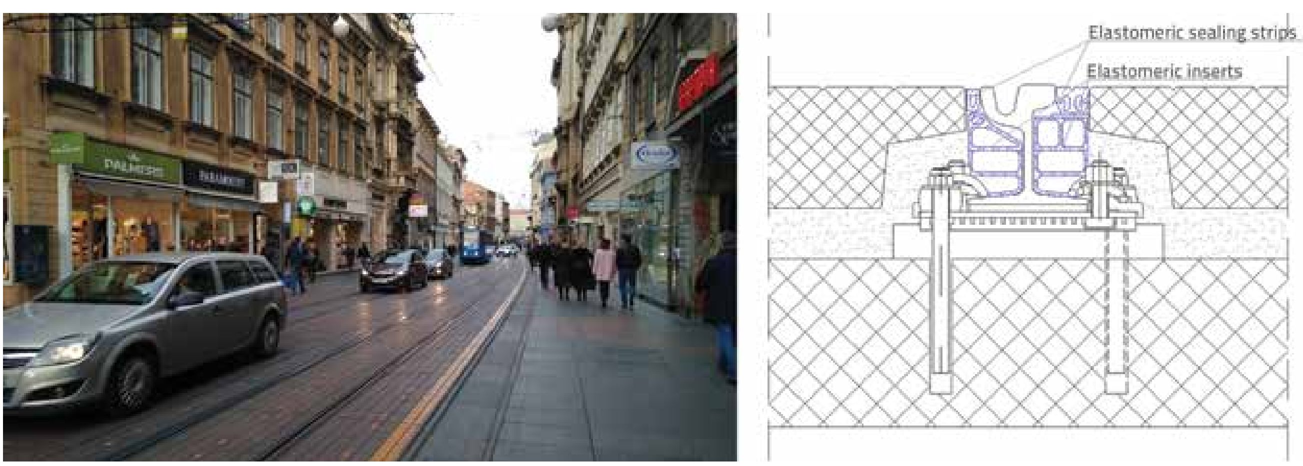

Figure 3. Example of track as a part of roadway (left), cross section of fastening point in case of tracks in roadway zone, DEPP fastening system (right)

If tracks are situated within the roadway zone they are closed with asphalt, reinforced-concrete slabs or in some other way, and are in this case called embedded tracks (Figure 3, left). In the city of Zagreb, rails for embedded tracks are insulated via elastomeric inserts at rail neck, while the bond between the rails and cover plates is ensured via elastomeric sealing strips (Figure 3, right) [7, 8]. As the road vehicle traffic is also operated on such embedded tracks, the tracks gradually deteriorate as can be seen through damage to reinforced-concrete slabs, deterioration of neoprene inserts next to rail web, and detachment of elastomeric sealing strips (Figure 4). Such damage results in penetration of water into the track system, and hence conditions favourable to the development of corrosion processes are created.

Figure 4. Reinforced concrete slab damage in track zone within a road system (left), deteriorated neoprene inserts next to rail web, absence of elastomeric sealing strip (right) [6]

In most cases, trams and underground railways use direct current of 550-750 V while suburban and urban railways use direct current of higher voltage (750-1500 V) [11]. Overhead contact lines with direct voltage of 3000 V are also in use. The alternating current of 50 Hz and 16 2/3 Hz is used in case of railways for long-distance transport [11].
The electricity coming from the power supply grid is carried to the electrical substation where it is converted via transformers and rectifiers into direct current with voltage as required for vehicle operation [10-12]. Each electrical substation supplies power to its part of the overhead contact line regardless of other parts, and the electricity is carried from the overhead line to the vehicle via pantograph [14]. In the same time interval, only one electrical substation can supply electricity to a vehicle on a tram infrastructure [5]. In most cases, the electricity is carried back to the electrical substation by rails and return lines forming connection between rails and the electrical substation. The use of rails to carry back electricity reduces track construction costs and makes unnecessary installation of an additional return conductor [10, 13]. The electricity required for tram operation is dependent on the way in which the vehicle is operated. Figure 5 (top) shows the diagram presenting dependence between the time, speed and distance travelled during vehicle operation, and Figure 5 (bottom) shows the current needed by the vehicle depending on the way it is operated. Three cases are analysed in this diagram: the vehicle accelerates in the time interval from 0 to 28 seconds, from 28 to 63 seconds the vehicle moves at a uniform speed, and from 63 to 84 seconds the vehicle decelerates and finally stops. If a vehicle moves at uniform speed or decelerates without the possibility for regenerative braking (return of electricity to the supply grid using engine as generator during braking activity [16]), its electricity consumption will be minimum, and hence stray currents will also be minimum. On the other hand, the consumption of electricity increases with acceleration, which will result in higher stray current values [17, 18]. When a vehicle accelerates, the quantity of stray currents will also depend on vehicle acceleration rate, i.e. the values will be greater with stronger acceleration.

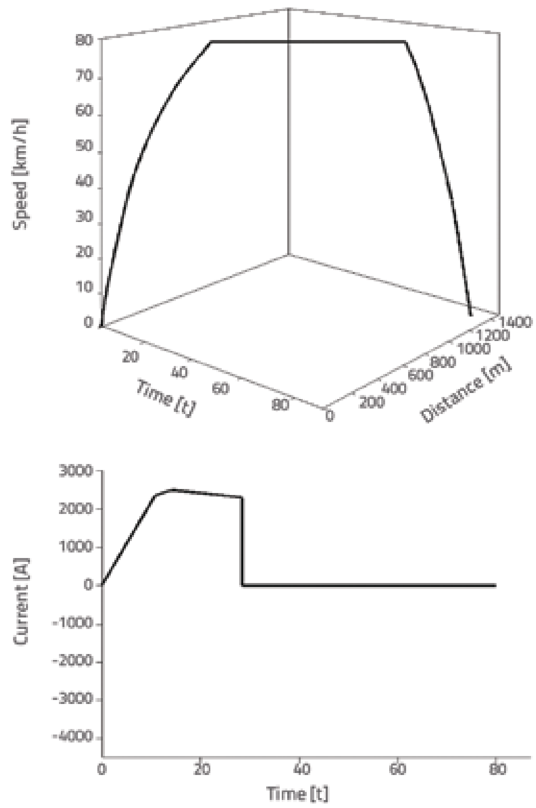

Figure 5. Diagram showing dependence between time, speed and distance covered during operation of a rail vehicle (top), intensity of current required by vehicle depending on type of operation (bottom), according to [17]

The floating system is most commonly used in electric rail systems. In this system, rails are not linked to soil at the electrical substation, i.e. the only link between the rail and soil is via the fastening system. When this system is used, high voltage can be generated in the rail which might jeopardise safety of rail infrastructure users. This can be solved by using voltage limiting device [16, 17]. In floating system, during return of electricity from the vehicle to the electrical substation, the electric voltage in the rail will appear as positive as the soil in near the rail vehicle, and negative in the vicinity of the electrical substation. The distribution of voltage along the rails will define points where stray currents will occur [17, 18].

2. Corrosion on urban rail infrastructure

2.1. Stray current corrosion

The electrochemical corrosion is a natural process during which the metal corrodes in contact with an electrolyte such as air, water or soil, and finally becomes dissolved [15, 19]. For the corrosion process to take place there must be a difference in potential between two metals, in which case one becomes the anode and the other the cathode. In addition, the metals must be electrically connected and immersed into electrolyte. The electrolyte ensures ionic conductivity, while the electronic conductivity is ensured between the anode and cathode [20, 21]. In the case of corrosion affecting rails in rail track, it is the result of contact between the rail steel and corrosive environment in which the rail is situated and the action of stray currents on the track. Corrosion due to stray currents is a special type of electrochemical corrosion that occurs due to release of current from a metal structure (electrical conductor). It has become a huge problem in recent times in urban track systems in which direct current is used as the source of energy. In the case of this type of corrosion, the anode and cathode form on the rail under the influence of current released from the rail, and the electrolyte is the corrosive environment in which the rail is situated.

When the current returns through rail from vehicle to electrical substation, an electric resistance is created in the rail (the resistance through which conductor material opposes the flow of current) and this resistance causes the difference in electric potential in the rail [24]. The difference in potential in the rail will depend on the way the rail is earthed. In the case of a floating system, which is nowadays in common use, the potential assumes positive values at the vehicle positions, and negative values in the vicinity of the electrical substation. If the rail is not fully insulated from soil, a part of the current will flow out of the rail at places of positive potential. This current, called stray current, finds the way of lower electrical resistance by which it will return to the source of electricity (Figure 6) [23, 24].

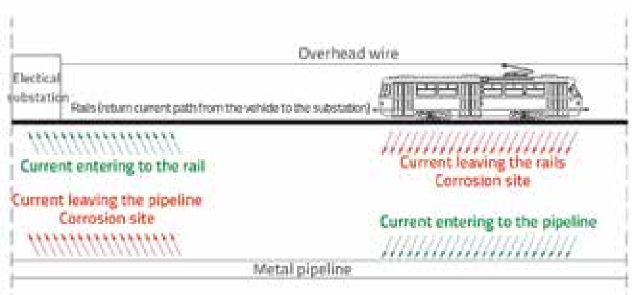

Figure 6. Development of stray currents on rail infrastructure

At places where the current leaves the rail, the corrosion processes will additionally be accelerated due to the action of stray currents [17]. The current released from the rail passes through the soil and enters a neighbouring embedded metal structure, such as a metal pipeline, and uses this medium as a return path to the source. The corrosion will also form at points where the current flows out of these embedded structures in order to go back to the rail or to the electrical substation, which can result in pipeline rupture [27]. Because of the above described effects, the corrosion caused by stray currents is a problem faced by rail infrastructure operators and by municipal infrastructure operators.

Out of all types of electrochemical corrosion, the corrosion due to stray currents is the greatest danger that may cause rail degradation in the track system, as well as degradation of municipal infrastructure situated in the vicinity of the track structure. For that reason, a special attention must be paid to the monitoring of track parameters that can provide information about the quantity of stray currents at a particular segment of the track [13]. These parameters are described in detail in Section 3.

Although the stray current occurring on rail track is extremely difficult to measure directly, various devices are currently available to make such measurements on municipal infrastructure situated near the railway track. In their paper [28], Mujezinović A. et al. describe field measurements of stray current at buried pipelines situated in the vicinity of tram infrastructure. The analysis of results has shown that the passage of tram vehicle causes high current values in pipelines. A diagram showing the current measured in a pipeline over a time interval of 1000 seconds is shown in Figure 7. Narrow peaks correspond to the passage of tram vehicles. The passage of seven tram vehicles can clearly be observed in the figure. In addition, in the case of the 24-hour measurement, the analysis of data points to an increase in the quantity of stray currents on pipelines in morning and afternoon hours when the rail system is subjected to highest loads [29]. Results obtained by the 24-hour measurement of pipeline potential are shown in Figure 8. This figure clearly shows that there is a significant increase in potential during peak hours [29].

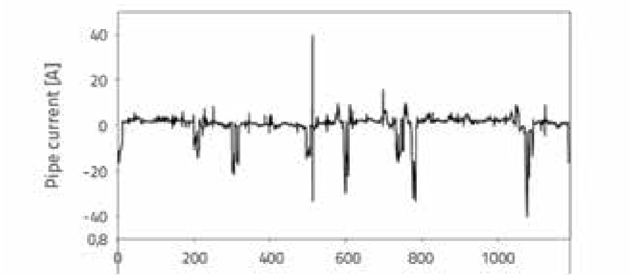

Figure 7. Results obtained by field measurement of current in buried pipelines, high values correspond to the passage of tram vehicles [28]

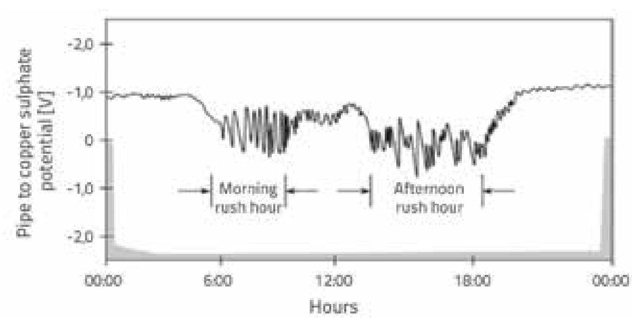

Figure 8. Pipeline potential measured during one day [29]

2.2. Examples of corrosion damage on rails

Corrosion mostly occurs at points where rail is fastened to the sleeper or to an appropriate support depending on the type of track structure, and this at the side of the rail foot (Figure 9) and at the bottom of the rail foot (Figure 10) [10]. It can be stated that corrosion occurs at the points of contact between the rail steel and some other part of track structure – sleeper or rail fastening system. The distance between the rail and support layer, as related to corrosion rate, is analysed in [30]. The height difference between the rail and support layer is defined by the type of sleeper, and in one case it amounted to 35 mm, and in the other to 71 mm. It has been demonstrated that in case of smaller distance the probability of rail corrosion is by 1.3 times higher, compared to a greater distance [30]. For that reason, greater attention must be paid to track control activities in case of smaller sleeper height, which also includes more frequent change of rails. In case of smaller height distances between the rail and track support, the rail comes into contact with water lingering on the track more frequently, particularly during heavy precipitation events, which enhances electrochemical corrosion processes.

Figure 9. Tested sample of corroded rail, loss of material from the side and top part of the rail foot: circled points are the points of concentration of highest normal stresses [31]

Figure 10. Tested sample of corroded rail, loss of material from the bottom side of the rail foot, circled points are the points of concentration of highest normal stresses [31]

If an appropriate track drainage is not provided for and the rail comes into contact with water lingering on the track, the rail corrosion will be even more pronounced [32]. In the case of the on-street running track (Figure 3), the corrosion rate and conductivity of stray currents will be enhanced through the action of deicing salt that is used to treat road surfaces in the following cases: when pavement is wet and air temperature is below 0 °C, immediately prior to the start of snowfall, when "ice rain" is expected and when adhesion to pavement is reduced [33]. Sodium chloride and calcium chloride, without sand or fine gravel, are used as deicing salt [33]. These chlorides dissolve in water and reach track structure very easily [21].

A rail sample extracted from the on-street running track embedded in the roadway, where rail corrosion has affected the entire surface of the foot, head, and web of the rail, is shown in Figure 11, while rail foot destruction at the fastening point is shown in Figure 12.

Figure 11. Corrosion affecting the entire length of rail foot and web, rail sample from street-running track

Figure 12. Rail foot rupture at fastening point on the street-running track

Corrosion at rail foot edges is manifested in the form of sharp edges, as can be seen in figures 9-12. The rail cross section is reduced due to loss of material at rail foot, which results in the accumulation of stress due to load, and in the widening of cracks. The resistance to shear and bending is reduced, and dynamic strength of the rail is impaired, which is why the rail becomes susceptible to fracture due to fatigue [27, 30]. In addition, the rail fastening force weakens, which increases the possibility of rail rollover or track widening in small radius curves. These occurrences can be detected by measuring track geometry under load using the track recording vehicle [30, 31].
Using a digitizer, Robles Hernandez F.C. et al. [21] created a digital image of rail samples, as shown in figures 9 and 10. The image was stored in the ANSYS software and a reliable numerical model was created. The model characteristics correspond to the characteristics of the corroded rail samples. The finite element analysis was conducted in order to determine stress distribution in rail samples. It can be seen on the sample shown in Figure 9 that great stress concentration is formed on corroded, sharp edges at the rail foot (Figure 13a and b) [21] . These values attain the elastic limit for rail steel and so corrosion damage at rail foot can result in rail foot rupture [19, 28]. In case of sample shown in Figure 10, the greatest stress concentration was observed at the start of narrowing of the rail foot, but stress values registered at this samples are much smaller compared to the first one (Figure 13c and d).

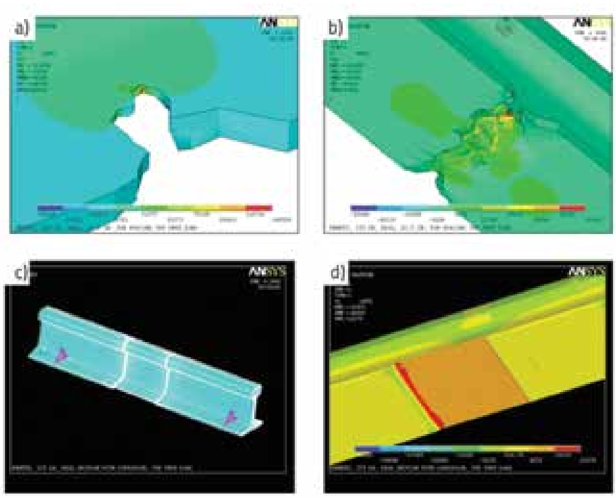

Figure 13. Stress distribution at the corroded rail foot, a) and b) first sample, c) and d) second sample [21]

3. Parameters that define quantity of stray currents on rail tracks

In modern railway systems, the measures used to reduce the effects of stray currents at the source can be divided according to the following two groups of parameters that define the level of stray currents [17, 33]:

- reduction of longitudinal electrical resistance of rails during return current path,
- increase of electrical resistance between rails and soil.

If a rail is not fully insulated, the electrical resistance of the support (load-carrying concrete layers) and electrical resistance of soil must also be taken into account [20].

3.1. Longitudinal electrical resistance of rails

Since rails are used as the conductor of current returning from the vehicle to the electrical substation, they will also be subject, just like any other conductor, to electrical resistance, i.e. to the resistance by which the conductor material opposes the flow of current [15]. The longitudinal electrical resistance of the rail defines the level of voltage that will be generated in the rail as the potential difference. A greater value of longitudinal resistance will result in greater voltage in the rail, and hence in greater value of stray currents [15]. Electrical resistance can vary depending on the type of steel out of which the rail is made, level of wear of rail head, and temperature in the rail [37]. The rail cross section deteriorates during rail use, which results in an increase in its electrical resistance. As to weather conditions, temperatures in the rail can vary by up to 40 °C, which can result in the change of resistance of up to 20 % [37]. Longitudinal electrical resistance also depends on conductor length – a shorter conductor results in a lower electrical resistance and hence a smaller difference in rail voltage will be generated due to shorter return path of the current (shorter distance between electrical substations) [24]. As longitudinal electrical resistance can vary to a great extent depending on the above mentioned parameters, the condition of rails should be monitored quite frequently.
According to [20], electrical resistance of rails ranges from 40 to 80 mΩ/km. This resistance to current flow can be reduced by using rails of greater cross section, and by welding rail ends to each other [24].

3.2. Rail-to-earth potential

The difference in potential that occurs in the rail when vehicles do not have the regenerative braking capability can be defined by determining the longitudinal electrical resistance of the rail, and based on the intensity of current needed for vehicle operation. In their work, Charalambous A. C. et al. [25] analyse distribution of potential in the rail as related to soil on a segment 1000 m in length.

Figure 14. Schematic of the observed track segment, vehicle 1000 m away from the electrical substation (ES)

They have assumed that an electrical substation is situated at the start of the segment, and that a vehicle requiring the current of 1000 A is located 1000 m away from the electrical substation (Figure 14). In addition, a constant electrical resistance of the rail along the entire section is assumed. It amounts to 40 mΩ/km for the track, and 20 mΩ/km for the rail, which means that voltage in the rail falls by 1 V/km for every 1 mΩ/km. Thus, the voltage difference of 20 V occurs on the observed section for the current intensity of 1000 A. In case of the floating system, this voltage difference will be manifested as +10 V at the vehicle position and -10 V at the position of the electrical substation (Figure 15) [25].

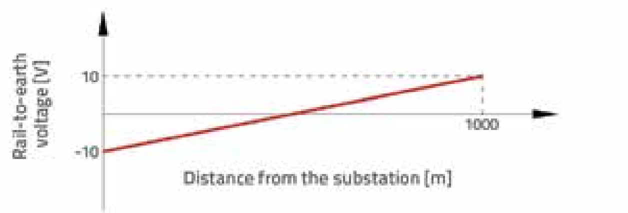

Figure 15. Difference in rail potential when one vehicle is 1000 m away from the electrical substation

If several vehicles are situated in the analysed zone, the potential in rail will be greater, which will result in greater value of stray currents. The case in which one vehicle is situated at every 250 m of the 1000 m section is considered (Figure 16). The distribution of potential valid in this case is presented in Figure 17.

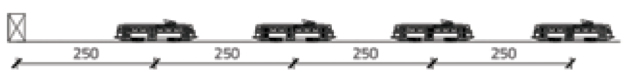

Figure 16. Schematic of analysed track segment, vehicles at every 250 m

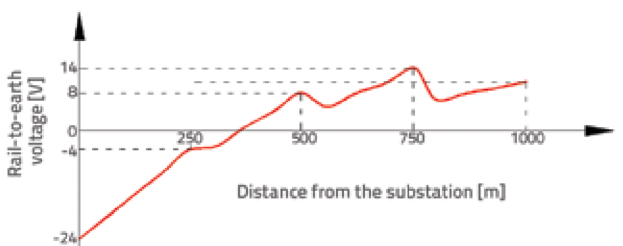

Figure 17. Distribution of potential along rail, vehicle at every 250 m from electrical substation

An anode zone is formed at the points of positive electrical potential in rails and, if the rail insulation is insufficient, a part of the return current is released from the rail and becomes stray current. On the other hand, a cathode zone is formed at places where the current returns to the rail, and this zone is characterized by negative electric potential. In such places, the rail is under cathodic protection and electrochemical corrosion will not develop.

As shown in figures 14-17, the rail voltage toward the soil that will develop along the observed track segment, and thus also the quantity of stray currents, also depends on the number of vehicles situated at the analysed segment at a given moment. In case of a greater traffic load, greater potential in the rail is registered, which also results in greater quantities of stray currents.

The greatest potential toward soil that can develop in rails, without harming the track by stray currents, is defined in standard HRN EN 50122-2:2011 [22]. In the case of open tracks and closed (embedded) tracks it amounts to $U_{RE} \leq +5$ V and $U_{RE} \leq +1$ V, respectively. If it is shown by rail-to-earth potential measuring over a 24 hour period that the rail potential exceeds the above values, then there is a possibility that stray currents will occur, and further measurements must be made to determine electric resistance between the rail and soil [38].

3.3. Rail-to-earth resistance in case of embedded tracks

The rail-to-earth resistance defines the intensity of stray currents at a particular segment of a track, and is defined by the way rails are insulated from fastening systems and sleepers. This insulation is realised via rubber pads positioned under rails at points in which rails are fastened to sleepers. However, as the water presence in track is more frequent in the case of embedded tracks, the level of track insulation must be continuous, and the insulation must cover the entire surface of the rail. This prevents contact between the rail and electrolyte such as moisture, water or chlorides that will linger in the track structure, and thus the electric resistance assumes high values. In many cases, rails are not sufficiently insulated so current leaks from rails and passes through the load bearing layer, where this layer behaves like an electricity conductor or electrolyte [39]. The standard [40] defines values of rail-to-earth resistance per unit of length. In the case of open tracks, the specific rail-to-earth resistance amounts to $R_{RE} \geq 2$ Ωkm, while in the case of embedded tracks it amounts to $R_{RE} \geq 0{,}4$ Ωkm.

The quantity of stray currents reduces with an increase in rail-to-earth resistance. However, high values of electric potential can be created in rail which can jeopardise safety of rail infrastructure users. It can be seen in Figure 18 that the quantity of stray currents will increase significantly if the value of rail-to-earth resistance falls below 10 Ωkm.

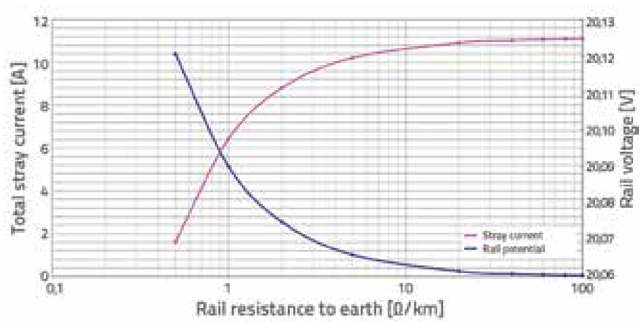

Figure 18. Relationship between electrical potential of rails and stray currents, as related to electrical resistance of rail toward soil [20]

According to guidelines 41], rails should be insulated in such a way to reach an equilibrium between the occurrence of stray currents and harmful rail-to-earth potential, i.e. to allow a certain

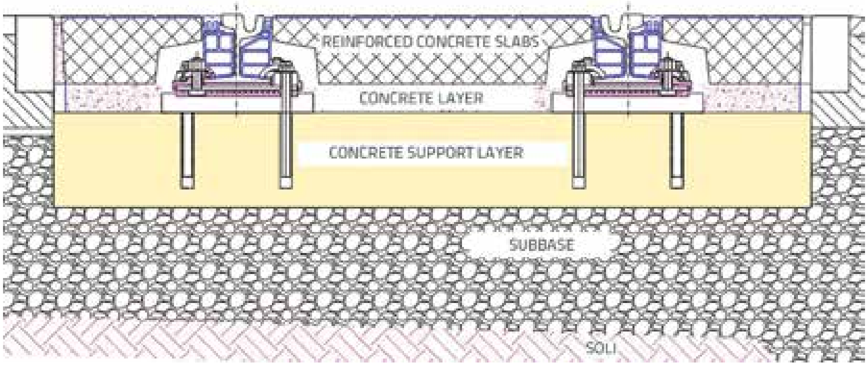

Figure 19. Cross section of track structure with the mentioned elements that define the level of electrical resistance between rail and soil in case of embedded track structure

quantity of stray currents to form so as to avoid achievement of high electric potential in rails. If rails are insufficiently insulated, the occurrence of stray currents will also be affected by electrical resistance of concrete in supports and concrete base courses, and by electrical resistance of subbase and the surrounding soil (Figure 19).

3.3.1. Electrical resistance of concrete layers of track structure

In order to reduce harmful action of stray currents, an insulation layer must be placed between the rails and soil. This layer can be realised, in addition to rail insulation, if the concrete used in the concrete base exhibits sufficient electrical resistance. Concrete is a porous composite made of various materials, and its electrical resistance is dependent on moisture [42].

In dry conditions, concrete acts as a poor conductor of electricity but, with an increase in moisture and with presence of water in track structure, it can become a very good conductor. Its specific electrical resistance varies from 10 to 108 kΩcm [40, 41].

In their paper, Geng J. et al. [44] analyse specific electrical resistance of concrete to which fly ash and slag have been added. The following samples were tested: B51 (0 % of fly ash and slag), B52 (10 % of fly ash), B53 (20 % of fly ash), B54 (25 % of fly ash), B55 (20 % of slag) and B56 (30 % of slag).

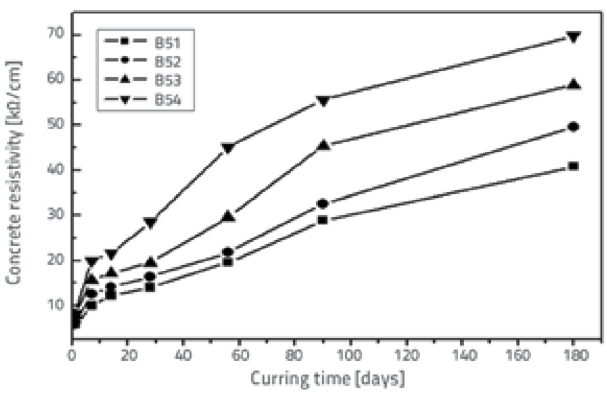

Figure 20. Specific electrical resistance of concrete with fly ash; samples: B51 (0 % of fly ash), B52 (10 % of fly ash), B53 (20 % of fly ash), B54 (25 % of fly ash) [44]

Specific electrical resistance was measured during 180 days, and the corresponding results are presented in diagrams shown in figures 20 and 21. The mentioned studies show that specific electrical resistance of concrete increases with the proportion of mineral content in binder.

Electrical resistance of concrete can also be influenced by the change in water/cement ratio. In their paper [45], Huajian L. et al. analyse electrical resistance of concrete at various water/cement ratios (0.31, 0.38 and 0.42). Their study reveals that electrical resistance reduces with an increase in water/cement ratio (Figure 22).

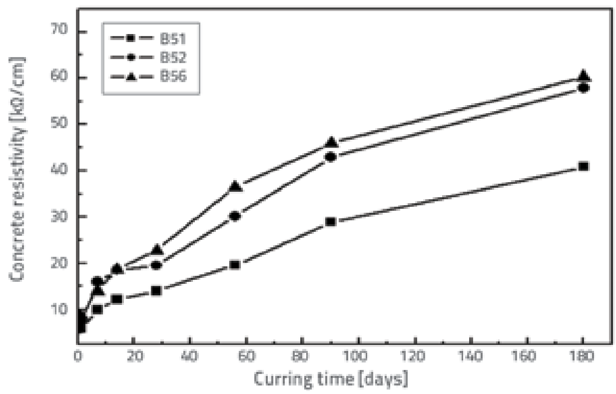

Figure 21. Specific electrical resistance of concrete with slag, samples: B51 (0 % of slag), B55 (20 % of slag), B56 (30 % of slag) [44]

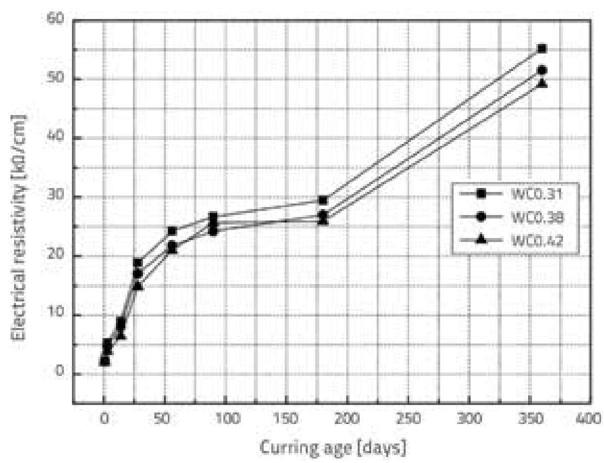

Figure 22. Specific electrical resistance of concrete at various water/ cement ratios (0.31 %, 0.38 %, 0.42 %) [45]

In case stray currents occur at a track structure segment, they can be reduced by increasing electric resistance of concrete in the support structure (base). Best results will be achieved by concrete in dry conditions, at reduced water/cement ratio, and by adding 35 % of fly ash or slag. Much better results can be expected in track structures by using concrete exhibiting an increased specific electrical resistance. Nevertheless, even in such case an adequate track structure drainage must be ensured to prevent accumulation of water.

In paper [46] the authors show that the compressive strength of concrete reduces in initial period when fly ash is added, but also that an increase in strength can be achieved by reducing the water/cement ratio. Thus the compressive strength can be increased by 8 MPa in case of fly ash content of 30 % when the water/cement ratio is reduced to 0,4. When the water/cement ratio is further reduced to 0.3 the strength can be increased by 23 MPa. Reduction in water/cement ratio implies the use of superplasticisers to ensure good workability of concrete. Also, it has been shown that the concrete strength increases over time due to pozzolanic properties of fly ash [46]. Furthermore, Maruthachalam V. et al. [47] have revealed in their research that compressive strength greater than that of conventional concrete can be achieved by adding slag to concrete.

3.3.2. Specific electric resistance of soil

In case of insufficient insulation of rails and other elements of the track structure, an increase in current leakage will also greatly be influenced by specific electric resistance of soil that reduces with an increase of moisture content in soil (Figure 23).

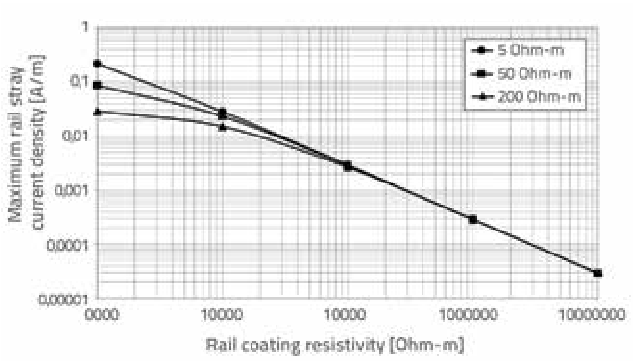

Figure 23. Quantity of stray currents as a variable of specific electrical resistance of insulation material of rail and specific electrical resistance of soil [20]

The influence of moisture content in soil on the quantity of stray currents is shown in Figure 24. Electric resistance of soil is influenced by moisture, and the following three samples were examined: wet soil (50 Ω/m), moist soil (100 Ω/m), and dry soil (150 Ω/m). It can be seen that smaller electrical resistance results in greater stray current values [17]. The mentioned studies have also shown that the specific resistance of soil increases by adding some materials (such as fly ash) to soil. This also results in the reduction of the value of stray current and electrical potential during acceleration of vehicles, when the value of stray currents is the greatest [17].

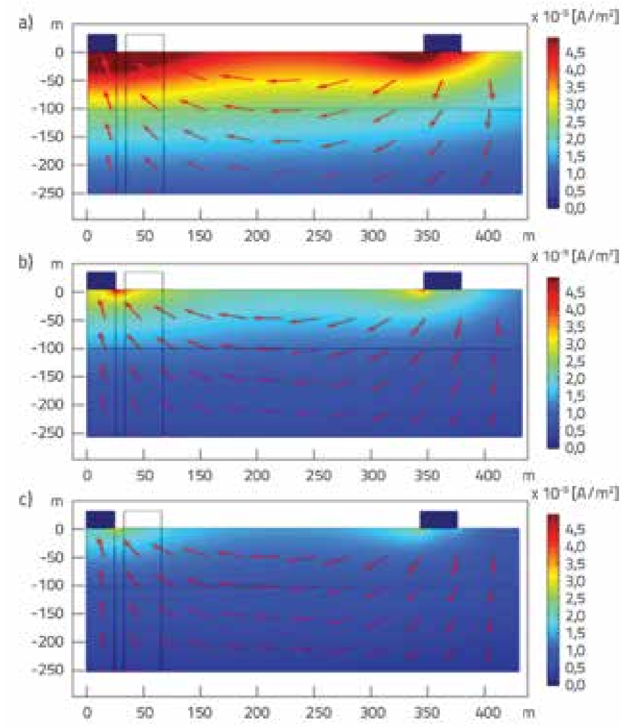

Figure 24. Distribution of stray currents in various moisture conditions: a) wet soil, b) moist soil, c) dry soil [17]

3.3.3. Determination of rail-to-earth resistance and intensity of stray currents

Several methods that are used for determining electrical conductivity between the rail and soil are described in EN 50122-2:2011 [40]. The method for measuring rai-to-soil potential using the reference electrodes placed in soil is presented in Figure 25. This measurement is not affected by traffic load so traffic does not have to be interrupted. The electrical potential of rail U_{RE} is registered between the rail and reference electrode E_2 that is placed in soil at some distance b from the rail R_2 [40]. The potential gradient U_{12} is registered by the second electrode E_1 placed at the distance "a" and by the electrode E_2. In their paper, Bongiorno J. and Mariscotti A. [48] indicate that, during rail potential measurements in urban areas, it is sometimes very difficult to find an adequate point for placing the reference electrode due asphalt surfaces. That is why asphalt electrodes $CuSO_4$ can be used as reference electrodes. However, the effect of buried pipelines and cables must be considered in such cases. The authors also recommend that such measurements be made in dry weather to avoid the influence of additional electrical conductivity due to soil moisture.

During this measurement, voltage values are registered by the measuring device, and the potential gradient ΔU_{1-2} can be represented as function ΔU_{RE}. At that, the slope of the curve obtained by linear regression represents the stray current transfer ratio m_{SE}. Before this measurement, it is also necessary to define the electric resistance of soil ρ_E near the electrode E_1. The distance a from the rail R_2 to the electrode E_1 must be at least 1 m, and the distance b must be so great that the electrode E_2 is not influenced by voltage gradient. The distance of 30 m usually suffices for this type of measurements in urban areas. However, it is necessary to check during the measurement whether the distance b is sufficient, or it has to be increased. In order to analyse insulation of rail from soil the measurement must be made at several locations, especially at places where track infrastructure intersects buried metal infrastructure facilities.

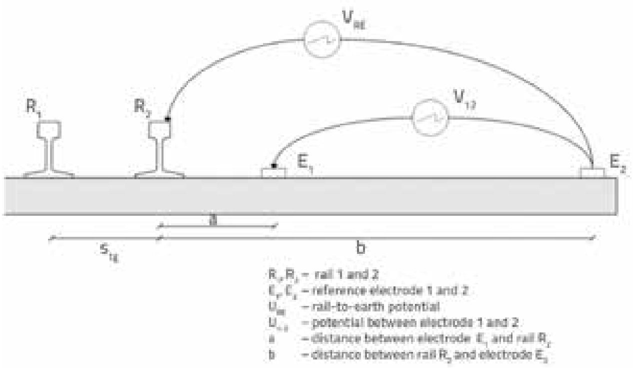

Figure 25. Measurement of potential between rail and soil [40]

The rail-to-earth conductivity soil is defined by the unit of length according to expressions given in [40] , separately for single-track and double-track railways. For single-track railways the rail to soil conductivity is calculated according to expression (1), while expression (2) is used for double-track railways:

$$G'_{RE} = \frac{m_{sr} \cdot \pi \cdot 2000}{\rho_E \left[\ln\left(b \cdot \left(b + s_{tg}\right)\right) \right] - \ln\left(a \cdot \left(a + s_{tg}\right)\right)} \tag{1}$$

$$G'_{RE} = \frac{m_{sr} \cdot \pi \cdot 1000}{\rho_E \left[\ln\left(\left(b + 5 \cdot s_{tg}\right) \cdot \left(b + 5 \cdot s_{tg} + s_{td}\right)\right) \right] - \ln\left(\left(a + 5 \cdot s_{tg}\right) \cdot \left(a + 5 \cdot s_{tg} + s_{td}\right)\right)} \tag{2}$$

According to [40], the intensity of stray currents that will occur at a particular location depends not only on electrical voltage in the rail but also on the rail to soil conductivity. It is expressed as follows (3):

$$I_s = U_{RE} \cdot G_{RE} \tag{3}$$

where:

I_s – stray current [A/km]
U_{RE} – electrical voltage in the rail [V]
G_{RE} – rail to soil conductivity [S/km].

In case the value of stray current along the rail amounts to less than 2,5 mA/m, there is no danger that track structure will deteriorate over a 25 year period due to stray current action [40].

Zaboli, A. et al. [13] used a numerical model to analyse distribution of stray currents at the rail ballast interface. They assumed in the model that the rail leans directly onto the ballast, and that the ballast rests on soil (Figure 26, left). It was established that the greatest quantity of stray currents occurs in the middle of the rail foot (Figure 26, right). This distribution of stray crurents across the rail foot occurs at rail fastening points, where rail leans via fastening system onto sleepers. Places of the highest quantity of stray currents obtained by the model correspond to the line of rail-foot failure at the fastening position, as shown in Figure 12.

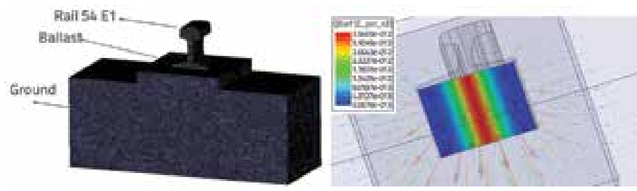

Figure 26. Numerical model used in the analysis of stray currents (left), distribution of stray currents across rail foot according to numerical model (right) [13]

The same team of authors analysed in [49] the distribution of stray currents across individual elements of fastening accessories, for various types of soil under the fastening system, with regard to specific electric resistance values: 100 Ωm (model A), 300 Ωm (model B), and 1000 Ωm (model C). It was established that the quantity of stray currents that leaves the rail will vary depending on the electrical resistance of soil, and that the highest values of current will be at positions of anchoring screws (Figure 27).

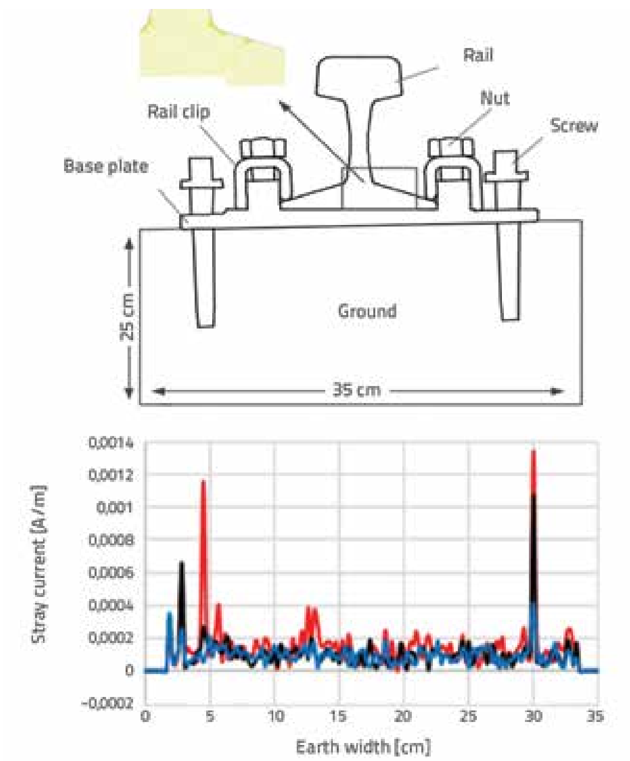

Figure 27. Distribution of stray current at rail fastening points for various values of electrical resistance of soil [49]

This coincides with the fact that, if good insulation of the rail and fastening systems is not provided at fastening positions, like in case of the fastening system ZG 3/2, higher quantities of stray currents will come out of rails and will be transferred through the underlying slab and anchoring bolts to the concrete load-bearing layers and to the soil. In the case of better insulated fastening systems, such as PPE and DEPP, higher values of electrical resistance between rail and soil will be realized, i.e. lower quantities of stray currents will occur. This coincides with the models B and C (Figure 27) where the evacuation of current from rail was reduced by using soil with higher specific electrical resistance.

4. Discussion

European standards that describe electrical safety at rail infrastructures are EN 50122-1:2011 [50] and EN 50122-2:2011 [40]. Protective provisions against electric shock on track systems using direct current for vehicle operation are defined in [50], while measures against the effects of stray currents on track infrastructures with direct traction are defined in [40]. In order to ensure timely detection of stray currents, track system condition must continuously be monitored, and parameters defining quantity of stray currents on track systems must continuously be checked. In effect, stray currents may cause great corrosion damage to metal parts of the track and, in extreme cases, rail corrosion can reduce life-time of rails to no more than one year [31].

The level of corrosion that occurs at rail foot is much greater than the level of corrosion measured in laboratory tests, which is why the only reliable method for determining level of corrosion on rails in use involves measurement of corrosion damage during rail inspections. This can be done in case of open and traditional track structures, but not in case of embedded track structures [31]. Considering great damage to rails and fastening accessories that can be caused by corrosion due to stray currents, and in addition to the control of standard parameters for determining condition of track infrastructure elements described in [51], it is also necessary to check the parameters that define the level of stray currents, which are described in this paper. Through all-encompassing and timely inspection of track structure, the life-time of railway superstructure, which are in fact the most expensive parts of rail infrastructure, will be extended [51]. To enable successful reduction of the quantity of stray currents on rail infrastructures, the following measures are currently most frequently applied [23]:

- reduction of longitudinal electrical resistance of rails,
- the best possible electrical insulation of rails against other track structure elements (increase of rail-to-earth resistance),
- preventing penetration of water into track structure,
- providing a sufficient number of electrical substations,
- providing an appropriate railway condition monitoring system.

4.1. Reduction of longitudinal electrical resistance of rails

The value of longitudinal resistance of rail must be very low. That is why rails must be connected to each other, which is nowadays performed by welding. In addition, longitudinal resistance can be reduced by using rails of greater cross section, and by connecting rails to one another in the track [21]. Rail monitoring activities must regularly be conducted as resistance can vary depending on the type of rail, type of steel used in the fabrication of rail, rail wear, and temperature [37].

4.2. Increase of rail-to-earth resistance

High value of rail-to-earth resistance must be ensured by insulating rail from soil and, at that, the quality of insulating material should be such that it does not deteriorate due to action of water that might remain in the track structure. Some of the methods used for increasing the rail to soil resistance include the use of insulation pads at fastening positions, insulation of fastening accessories, and coating of rails and supporting slabs by insulating membranes at places where the track is situated in the street (street running track). In any case, it is important to provide for an adequate track drainage, and to regularly conduct maintenance activities. In case of open track structures in which rails are placed onto sleepers, the use of plastic composite sleepers is suggested to insulate track from soil. In effect, as composite sleepers have a significantly greater electrical resistance compared to other types of sleepers, the use of these sleepers will prevent leakage of stray currents from the rail, thus reducing corrosion at the rail foot [31]. Electrical resistance testing of plastic composite sleepers was conducted in [31] and it was established that their resistance amounts to 65 kΩ, which is by 3.25 times more compared to minimum 20 kΩ defined in specifications of the American Railway Engineering and Maintenance-of-Way Association (AREMA).

4.3. Preventing water penetration in track structure

It is not easy to prevent water penetration at urban track structures, and especially at on-street running track structures. The most frequent example of a track element degradation at tram infrastructure in Zagreb is shown in Figure 4. This degradation permits free penetration of water into the track structure. As can be seen in that figure, the reinforced-concrete cover slab is damaged, and elastomeric sealing strips that are placed next to rail have fallen out. Water can be stopped from penetrating into track structure over a longer period of time through implementation of new sealing technologies. Thus, in case of track rehabilitation at the Savska cesta road section in Zagreb, a fill material was used instead of traditional elastomeric sealing strips (Figure 28) [9]. This material is bonded on the one side with the rail, while on the other side it is connected with the reinforced-concrete cover slab and, hence, the rate of water pouring along the rail into the track structure is reduced, and so the quantity of stray currents is reduced as well. Just like wet soil (Figure 24), wet track surface is also a good electrical conductor and, if rail is not fully insulated, stray currents will flow through the rail and fastening systems and into the support structure and further down into the soil, as shown in figures 26 and 27. However, stray currents will be reduced if adequate measures are taken to reduce penetration of water into track, and if water lingering is prevented by appropriate drainage.

Figure 28. Placing fill material instead of sealing strips at Savska street tram section in Zagreb [9]

4.4. Distance between electrical substations

Reduction of distance between electrical substations, i.e. the use of several return cables between rail and electrical substation, is also recommended as a measure for reducing the quantity of stray currents. In this way, the return path of current from vehicle to electrical substation is reduced and the creation of high voltage in rail, an hence also of stray currents, is prevented. However, the quantity of stray currents is not greatly affected by the distance between electrical substations in the case of high electric resistance between rail and soil (Figure 29).

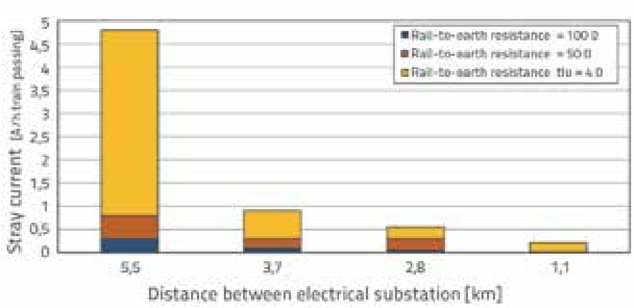

Figure 29. Reduction of stray currents through increase in rail-to-earth resistance and through smaller distance between electrical substations [20]

4.5. Costs caused by stray current corrosion

Stray current corrosion is the fastest form of electrochemical corrosion and, in addition to bringing degradation of track elements, it also causes damage to municipal infrastructure situated in the vicinity of track infrastructure, resulting in frequent pipeline ruptures, and hence in great repair costs. Corrosion due to stray currents in concrete reinforcement was analysed in [52], and it was established that this corrosion is much more harmful compared to chloride action. Furthermore, many analyses were conducted to estimate damage to reinforcement on bridges and viaducts. It was established that damage caused by stray currents is very high, and that appropriate protection measures must be implemented to keep these structures in good state of repair [53]. The analysis of costs incurred through the action of stray currents at several track infrastructures is presented in [54]. The operators that submitted data on rail infrastructure corrosion costs declared that these costs are of minor significance, and that the damage is restricted to rails and fastening accessories. However, if the damage to structures situated in the vicinity of rail infrastructure is taken into account, then the costs become much greater. For instance, annual costs caused by corrosion due to stray currents amount 500 million dollars annually in the US. In order to reduce these costs, the best option is to apply stray current reduction measures at the source (track structure), and to implement measures aimed at increasing rail to soil electrical resistance. There are currently many ways for reducing stray currents, such as by providing smaller distance between electrical substations, and by continuous insulation of rails. The implementation of these measures is burdened by considerable costs, and some of the measures can be used in case of new track structures only. It is precisely for this reason that a strong emphasis is nowadays placed on track maintenance and adequate drainage, the aim being to increase rail to soil electric resistance, reduce quantity of stray currents, and extent useful life of all structures affected by this problem. In addition, stray currents can even be reduced by small investments such as through better insulation of fastening systems and by making track sealing improvements.
In response to great direct and indirect costs arising from stray current action, the introduction of new, better insulated rail fastening systems called Zagreb 21 CTT has been initiated in the city of Zagreb. This fastening system is characterised by insulation of individual elements, such as anchoring screws and setting pads. In addition, in order to curb down penetration of water into the track structure, the improvement of track sealing is considered by means of fill material (Figure 28) instead of traditional sealing strips [9, 55].

5. Conclusion

It is almost impossible to avoid electrochemical corrosion of rails, i.e. the only way to avoid such corrosion would be by complete insulation of rails. Corrosion due to stray currents is the most destructive form of corrosion. The greatest destruction by corrosion can be seen at embedded track structures as they present the greatest difficulties when attempts are made to obtain high level of electrical resistance between rail and soil. A substantial loss in material, and rail foot narrowing at points were rails are fastened to sleepers, are problems that have been observed on many rail infrastructures all over the world. Such loss of material results in rupture of rails while also jeopardising safety of rail infrastructure users. Based on previous experience, operators have estimated what would be the maximum loss of material at rail foot that would not endanger integrity of rails and safe operation of traffic. Nevertheless, it is very difficult to estimate useful life of rails as it can, in highly unfavourable conditions, be brought down to no more than one year. The useful life of rails and fastening systems is additionally reduced by the action of stray currents, which also jeopardise structures situated near the rail infrastructure (pipelines, bridges, viaducts), which results in very high maintenance and repair costs.

Although stray currents are very difficult to measure directly, accurate information about rail condition, enabling the operator to decide whether to protect or replace the rail, can be obtained by measuring other parameters such as electrical resistance between rail and soil, and longitudinal electrical conductivity of rails.

Finally, to enable successful reduction of the quantity of stray currents on rail infrastructures, it is necessary to continuously monitor condition of rail infrastructure, measure rail to soil potential, and keep the track structure dry through proper drainage.

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