Voltage distribution indices method to analyse the performance of various structures of stray current collectors in direct current transit lines

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Abstract
The stray current produced by a direct current (DC) transit system leads to the corrosion of rails and metallic structures buried under and around the metro line. One practical approach to diminish current injection into buried structures is to implement stray current collectors underneath the rail. An analytical method is proposed herein using voltage distribution indices (VDIs) to calculate the voltage and current collection level of each collector located under the rail soil, and the solutions are validated by comparing with modelling results. The proposed method helps to achieve the voltage of different points under the ground and the current reaching the collectors using a circuit model, without facing the limitations of practical methods, as a supplementary study for experimental tests. Moreover, the effect of different arrangements of collectors under running rails is modelled. The analytical method is deployed considering two objectives, that is stray current collection by the conductors and a reduction in the installation cost of the conductors. Various arrangements of stray current collectors are compared and evaluated. Using integral and matrix equations, current density and potential at different points under the soil are calculated and the obtained results are compared with European (EN) standards.

1 | INTRODUCTION

The use of running rails as the current return conductor to the negative busbar of supply substations in DC railway systems causes numerous problems, including the generation of stray current and an increase in the rail-to-earth voltage level. Stray currents that crawl through rails into the earth can flow through building foundations, pipes, and other underground metallic installations with less resistivity with respect to the soil to reach the negative terminal of the substation. The points at which current enters/leaves the metallic structure are called the cathodic/anodic regions, respectively. The current leaving the anodic region causes the corrosion phenomenon on the metallic structure. Various methods have already been used for stray current modelling in railway transit systems. In most of the literature and simulations, such as in [1, 2], the metro system is presented as resistive grids and the mathematical equations are given based on the traction substation current, rail track resistance, the distance between the train and substation, the resistance between the rail and earth, and stray current. In [3, 4], the rail voltage and current are evaluated under different speeds and accelerations and the performance of rail potential control devices for controlling rail voltage is assessed. The authors in [5–7] measured the rail voltage and stray current at a point in which the train is present and then introduced an electrical model to calculate the stray current. Furthermore, to minimise the stray current and the potential level of different points on the rail under various situations of the metro, an appropriate earthing system is proposed. In [8, 9], resistive grids are simulated and dynamic evaluation, especially for calculating the maximum potential increase in rail transit systems, and analysis of different earthing modes on the rail potential and stray current are carried out. Reference [10] presents a dynamic model that is a combination of the ideal and real-world cases, and integrated walls are considered for the tunnel body to prevent the stray current from leaving the established fence and
damaging the structures. Different earthing systems and their performance with respect to the corrosion effect of stray currents in the vicinity of the traction substation, as well as in middle points between two stations, are evaluated in [11, 12]. The elements underneath the rail are accurately studied in [13, 14] from electric and magnetic standpoints, and capacitive and ohmic resistors are measured besides microscopic calculation of the stray current. The maximum corrosion occurs at the joint area of two adjacent metals and taper points, so the greatest possible cathodic protection needs to be performed at such points. Ref. [15, 16] presents a multi-layer soil model to reduce the destructive effects of the stray current. The metallic pipe buried at short distances from the negative terminal of the traction substation is protected and using a diode the available current flows in one direction. A metro tunnel including metallic equipment and a metallic loop along with the proposed current collector system and a stray current transmission cable under each running rail is proposed in [17, 18]. By calculating the voltage drop and stray current level, the amount of current collection by all buried metallic components is obtained. In [19, 20], the overvoltage protection device (OVPD) is installed near the substations and between the ground system, the running rail, and the negative busbar, and continuously measures the potential difference between the rail and the ground. If the voltage level of the rail is lower than the specified voltage of the equipment, the device remains off and the system ungrounded; and, when the voltage exceeds a certain value, the thyristor gate pulses and the contactor closes and the system becomes grounded and the rail voltage becomes close to zero. Moreover, a method is introduced to measure rail voltage. In [21, 22], the rail line and traction power substation (TPS) elements are simulated as several parts and piece by piece in CDEGS software, and after determining the train current, the rail potential and the stray current are obtained in the proposed model. Refs. [23, 24] investigated the effects of stray current on metro warehouse equipment as well as on AC power grid, which includes corrosion of ground networks, harmonic increment, and incorrect protection. The mentioned references addressed the stray current collection, rail voltage control, and different earthing systems of the rail. However, important aspects such as the material used for the conductors, the arrangement of collectors, and the economic cost of constructing the stray current collection grid have not been studied. The arrangement and distance between collectors under the running rails significantly influence their current collection capability. With regard to the importance of these topics, the an analytical method by deploying matrix elements (voltage distribution indices, VDI) is introduced herein. Experimental calculation of voltage is costly and time-demanding; but the voltage of all considered points under the soil can be obtained using voltage distribution indices. Matrix elements are of resistance dimension. The value of stray current absorbed by conductors can be calculated via the calculation of the resistance across the electrodes under the soil more straightforwardly and more accurate than the modelling method or experimental experiments. Additionally, different arrangements of conductors are simulated and compared with each other to obtain the maximum stray current. Moreover, the economic cost of installation of different arrangements for stray current collection systems is calculated. In summary, the contributions of the study are as follows:

- Presenting a novel VDI matrix method and calculation of the current rate reached to any buried conductor, which enables the calculation of potential levels of all specified electrodes under the soil using the proposed method;
- Analysis and comparison of various arrangements of collectors in terms of current absorption, using the proposed method;
- Economic analysis of procurement and installation cost of different collector structures.

Section 2 applies the proposed model to a sample under study. Section 3 presents mathematical and analytical relationships of the VDI method to determine voltages and currents of different points on the buried conductors. Section 4 deals with experiments that validate the proposed method. Section 5 studies the simulation results using software and compares them with that of the proposed method to verify the validity of the suggested approach.

2 | PROPOSED METHOD

DESCRIPTION

Modelling is carried out in the MALZ module of CDEGS software. The MALZ module permits currents to be injected and collected at various points in a grid consisting of conductors buried in the soil. The current of each conductor in the grid is computed separately so the stray current and voltage distributed throughout the system are modelled. Specifically, 1 km of the metro tunnel has been simulated along the length of the track, assuming the track is uniform and standard.

2.1 | Methods for controlling and reducing stray current and rail voltage

Measures that can be taken to control stray current and rail voltage in DC rail transit systems include: increasing the electrical resistance between the rails and the ground by insulating the rails from the ground, reducing the longitudinal resistance of the rails, applying an effective earthing system in the substation, and installing a stray current collection system between adjacent rails and steel structures. Electric insulation is usually used between rails and fixings and between fixings and traverses. To prevent corrosion of metallic structures, methods such as cathodic protection are widely used for corrosion protection of gas transmission and distribution pipelines, petroleum materials, and skeletons of important structures. This type of prevention being buried at the structure site is called secondary protection. Nonetheless, there is another method that prevents the stray current from reaching the metallic
structure where the stray current collector is used, called primary protection.

2.2 Stray current collector

To reduce the stray current corrosion risk, longitudinal conductors can be used along the entire tunnel path, which plays the role of stray current collectors, the conductivity and current collection levels of which should be the maximum value possible. These longitudinal conductors are used according to the ENS0122-27.2.2 standard [25]. Although the surrounding structures can be insulated from tunnel sections, it is not possible to achieve complete control of stray currents. Proposed schemes according to environmental conditions and economic feasibility are as follows:

1. Use of separate steel rods: These separated rods are mounted underneath the running rails in a straight line and in parallel. They are also connected to each other at distances of 50 m using a rod with the same specifications to further strengthen the rods. In parallel, two cables are stretched on either side of the rails and connected to stray collector rods every 100 m using a cable. The size of the two cables and their placement can vary widely.

2. Use of copper plate: A copper plate that is 2–5 mm thick and 20 cm wide is another type of stray current collection system that extends beneath each rail and along the entire route. The material of these sheets is copper, so as to provide high conductivity. Problems for these types of collectors are twofold: the first is the lack of strength and the possibility of rupture of the shield due to the high weight of rails and trains, and the second is that these metals are oxidised underground due to high humidity and they change slightly in colour. This decreases the conductivity of their outer surfaces and their ability to absorb current.

3. Use of mesh grid: This grid consisting of steel bars bonded together 10 cm apart helps in absorbing high stray current and also contributes to the strength of the rail bed. The grid can also be coupled with a coated cable to transfer the collected current. The steel rods are connected at every 100 m to the coated cables carrying the stray current (Figure 1).

Another suggestion is to use a rod with steel core and copper coating because the rod with steel core provides acceptable strength under the rail pressure and also can absorb more current thanks to its copper coating. More importantly, due to the higher reactivity of iron than copper in the soil, the steel core becomes corroded in the long term and the copper is later oxidised and remains conductive.

2.3 Description of the substrate model

To reduce the amount of injected current from the rails to the ground, the substrate material must be selected with the best resistance ($10^{14} \, \Omega \cdot m$) to minimise the amount of stray current. In modelling, three regions are considered for the environment around the rail. Region 1 is the air inside the tunnel with high resistance that prevents stray current flow from the rail upwards or down the tunnel ring through this area. Region 2 is made of concrete and comprises components of the stray current collection system which is assigned a resistivity of 200 $\Omega \cdot m$. For the third region, that is the track-bed soil, the worst possible case and the maximum moisture are considered and is assumed to have a resistivity of 15 $\Omega \cdot m$. The regions are illustrated in Figure 2.

The data related to the components and other corresponding data, including the material and cross-sectional area of the materials used are shown in Table 1.

3 ANALYSIS OF THE VDI METHOD

Numerical and analytical methods can be used to calculate the voltage levels of buried conductors in the soil and the amount of current collected by each buried conductor, thus achieving the optimal arrangement of stray current collectors. Numerical calculations are point-based and approximate, and their use in 3D problems demands a long computation time. Analytical methods should be used to accurately calculate voltage and current values in buried conductors. Using the VDI method, integral relations, and image theory, one can obtain the current density ($J$), electric field ($E$), and potential ($\phi$) by means of Equations (1)–(3) at various points inside the soil and on the surface of buried conductors in the soil [26].

\[
V(r) = \int_{\gamma_1}^\gamma \rho J(r)dr \tag{1}
\]

\[
E(r) = \rho J(r) \tag{2}
\]

\[
J(r) = \frac{2I}{4\pi \gamma_1^2} (\gamma_1 - r_1) + \frac{2I}{4\pi \gamma_2^2} (\gamma_2 - r_2) \tag{3}
\]

Internal and external conductor radius are, respectively, $r_1$ and $r_2$ The conductor and its image are both considered in an
environment with a resistivity of $\rho$. The current passing through the conductor is $I$. The conductor-to-ground resistance of the horizontal electrode and the metal strip is obtained by considering the spatial coordinates of each element of the injector conductor and collector. Identical to the modelling of the rail in the soil, in the analytical section, the rail in the soil and the collectors underneath it are considered. To use this method, the body of the inductors must first be divided into small segments. Then the voltage relations of the various points and the current between these elements are found. The running rail is divided into $n$ small elements and the current $I_j$ leaves the surface of section $j$ and spreads in the soil, as shown in Figure 3.

Now if the stray current leaves one conductor (rail) element with a centre at $(x_j, y_j, z_j)$ that is located in the ground, the following is used to calculate the voltage ($V$) at element $i$ of the collector with coordinates $(x_i, y_i, z_i)$:

$$V_i = \sum_{j=1}^{n} f(x_i, y_i, z_i, x_j, y_j, z_j, \sigma) I_j$$  \hspace{1cm} (4)

where $I_j$ denotes the total current flowing out of the element $j$. Both the injector and the absorber are longitudinal conductors (in modelling rails in the soil are considered); the substrate has a specific conductivity $\sigma$, the length of the injector conductor is $2L_1$, and the length of the collector conductor is $2L_2$ along the $x$-axis, where $I_j$ denotes the total current flowing out of the element $j$.

Considering individual elements $i$ and $j$ of the collector and rail, respectively, the function $f$ can be obtained from the following equation [27]:

$$f = \frac{1}{16L_1L_2 \pi \sigma} \left[ F(x_i - x_j + L_1 + L_2, B_x^-) - F(x_i - x_j + L_1 - L_2, B_x^-) + F(x_i - x_j - L_1 - L_2, B_x^-) + F(x_i - x_j + L_1 - L_2, B_x^+) - F(x_i - x_j + L_1 + L_2, B_x^+) \right]$$ \hspace{1cm} (5)

where $F$ is the computational function of the two elements of conductor and rail, and is defined by:

$$F(t, u) = \ln \left[ t + (t^2 + u^2)^{0.5} \right] - (t^2 + u^2)^{0.5}$$ \hspace{1cm} (6)

where $t$ and $u$ are the arguments of this function. Moreover, the parameters $B_x^\pm$ in Equation (5) are obtained by:

$$B_x^\pm = \left[ (y_j - y_i)^2 + (z_i \pm z_j)^2 \right]^{0.5}$$ \hspace{1cm} (7)

Function $f$ in Equation (4) can be interpreted as voltage distribution index of the element $i$ of the collector with respect to the element’s injection currents of the rail ($I_j$). Therefore, we define:

$$[VDI]_{ij} = f(x_i, y_i, z_i, x_j, y_j, z_j, \sigma)$$ \hspace{1cm} (8)

where $[VDI]_{ij}$ is defined as the voltage distribution index between the two elements $i$ and $j$, where its dimension is ohm. The $n \times n$ dimension matrix VDI, in which its elements are
mutual resistances between the elements of the conductor and elements of the rail, is obtained as follows:

\[
VDI = [VDI_{ij}] = \begin{bmatrix}
R_{11} & R_{12} & \cdots & R_{1n} \\
R_{21} & R_{22} & \cdots & R_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
R_{n1} & R_{n2} & \cdots & R_{nn}
\end{bmatrix}
\]

(9)

The VDI matrix arrays are voltage distribution indices with resistance dimension. Therefore, Equation (4) can be rewritten in its matrix equivalent form:

\[
V = VDI.I
\]

(10)

where \( V \) and \( I \) are the \( n \)-dimensional voltage and current vectors of the conductor and rail elements, respectively:

\[
V^T = [V_1^T V_2^T \ldots V_n^T]
\]

(11)

\[
I^T = [I_1^T I_2^T \ldots I_n^T]
\]

(12)

The total current injected from the first conductor (i.e. the rail) can calculated by:

\[
I_T = \sum_{j=1}^{n} I_j
\]

(13)

and the voltage at the central point of the conductor is equal to:

\[
V_{cent} = \frac{1}{2L_2} \int_{x=-L_2}^{x=L_2} V(x,y,z) \, dx
\]

(14)

where index cent refers to the central point of the collector. The potential of all the elements of the collector is obtained by entering their coordinates into Equation (14). If the voltage of each element is known, then the potential of all points of the collector conductor will be known. The matrix method is relatively simple, but to increase the computation speed and to avoid the computation of bulk inverse matrices, the real current can be approximated as a step function using Equations (15)–(17), which is a combination of integral and matrix relations. Also, the current density of elements is assumed constant but unknown. In the next step, the relationship between the voltage of each point and the current of all components is obtained. An integral is taken along the length of the conductor and, subsequently, the matrix is used, which is why it is called the combined (integral-matrix) method [28].

\[
V_i = \sum_{j=1}^{n} R_{ij}I_j
\]

(15)

\[
V = \sum_{j=1}^{n} R_{j}I_j
\]

(16)

For different parts \( j = 1,2,\ldots,n \), this voltage is obtained based on the stray current of each part, and by using the above equations, if the voltage level is specified, \( I_j \) can be calculated and the resistance between the two conductors will be obtained. To calculate the voltage of each part of the earthing system such as point A we will have:

\[
V(A) = \sum_{j=1}^{n} R_{tj}I_j
\]

(17)

where \( R_{tj} \) is the VDF between elements \( j \) and \( i \). Thus, the voltage \( V1 \) to \( Vn \) is calculated from the underground collector and the current flowing in these conductors is obtained by dividing the potential difference between \( V1 \) and \( Vn \) on the longitudinal resistance of the conductor. Therefore, to avoid the flow of the destructive current into the structure, the placement and arrangement of collector conductors can be determined based on the resistance and potential of these conductors to prevent corrosion of the substrate. Also, the number of horizontal and vertical conductors required is obtained and applying additional layers of mesh grid will not occur.

### 3.1 Determining the number of longitudinal and transversal branches

To determine the number of longitudinal and transversal conductors of the mesh grid the earthing system of high-voltage (HV) substations can be imitated and, taking into account several assumptions, a new method for determining the number of branches of the collector system to meet the two objectives of absorbing the stray current and reducing collector installation costs is presented. Conductor current, GPR, and the resistance between conductors are calculated according to IEEE 80 standard [29]. The difference between an HV substation and a metro substrate is that the purpose of the substation is to reduce the step voltage and contact voltage, but in the metro, the mesh system has a duty to absorb the stray current flowing into the soil so that the corrosive current cannot flow into the adjacent structure. The objective of this arrangement is to minimise the cost function and the collection
of stray current by conductors is also considered as a constraint. According to Equations (8)–(17), the current collected by a buried conductor in the soil can be obtained as follows:

\[ I_{\text{collected}} = \sum_{i=1}^{k} I_i \]

and the current \( I_{\text{stray current}} \) as follows:

\[ I_{\text{collected}} \geq \alpha I_{\text{stray current}} \]

as the current reaching the foundation of sensitive structures should be negligible and considering the practical examples and other references, if the stray current collection system can collect \( \alpha = 0.75 \) of the stray current, the current flowing to the buried structure will be less than 1 mA and this low current does not lead to corrosion [17]. Therefore, the first condition is to collect the dominant part of the total stray current by the stray current collection system. As a result, the collected current must have its maximum value. The cost function includes steel bar cost \( \langle C_{\text{cond}} \rangle \) (cost of horizontal conductors), construction labour cost \( \langle C_{\text{trench}} \rangle \) (installing and backfilling conductors and rods), and connection cost \( \langle C_{\text{connect}} \rangle \), which should be minimised [29].

\[ \min \text{Cost}_{N_1,N_2} = \langle C_{\text{cond}} \rangle + \langle C_{\text{trench}} \rangle L_{\text{cond}} + \langle C_{\text{connect}} \rangle (N_{\text{exoth}}) \]

where:

\[ L_{\text{cond}} = (N_1 + 1).L_1 + (N_2 + 1).L_2 \]

\[ N_{\text{exoth}} = (N_1 + 1).(N_2 + 1) \]

\( N_1 \) and \( N_2 \) express the numbers of transversal and longitudinal branches of the mesh grid, respectively. Moreover, \( L_1 \) shows the length of the transversal branch which is generally less than 2 m and \( L_2 \) is the length of the longitudinal branch which is assumed less than 4 m for any particular point. The following constraints are set for \( N_1 \) and \( N_2 \):

\[ \frac{L_1}{0.4} \leq N_1 \leq \frac{L_1}{0.05} \]

\[ \frac{L_2}{0.4} \leq N_2 \leq \frac{L_2}{0.05} \]

The designs of the mesh grid are presented in Table 2.

4 VALIDATION OF THE PROPOSED VDI METHOD

To validate the proposed VDI method, its results are compared with two reference papers that have utilised practical tests to evaluate the voltage distribution from around the metro rail during current flow. Additionally, the test systems used in these two reference papers are simulated in CDEGS software and are employed for validation purposes.

4.1 Case study I

Ref. [30] tests the DC metro of Shanghai, China, which is in the vicinity of gas pipelines. The gas pipeline is at a depth of 2 m underground parallel to running rails, with a traversal distance of 10 m from the rails, and the resistivity of the bed soil is \( \rho = 15 \Omega \text{m} \). As the direct measurement is impractical, \( \text{Cu/CuSO}_4 \) was used as the pipe electrode for testing. Two points P1 and P2 at a 100 m distance from each other were specified on the buried gas pipeline, as depicted in Figure 4. The rest of the environment data are available in [30]. Also, a monitoring system was adopted to observe current and voltage signals. Voltage measurement of the pipe was carried out for a duration of several hours.

In this reference, the injector and absorber conductors are both longitudinal. Elements of the matrix VDI are obtained considering the coordinates of both origin and destination points, the conductivity of soil, and function if [Equation (5)]. The potential of all elements of the gas pipe is calculated by inputting their coordinates, and the potential of the considered point on the pipe is obtained based on Equation (14). Moreover, the structure under study in this reference is modelled according to their exact specifications in CDEGS software, and the voltages of the pipe at points P1 and P2 are provided. Output test voltage voltages of ref. [30], CDEGS software and the proposed VDI method are shown in Figure 5. The results, which indicate the pipe voltage with respect to soil voltage at different times, can be compared. As per Figure 5, the proposed method has successfully and accurately calculated the voltage of the considered points. According to this figure, the maximum error of the proposed method in comparison to that in [30] is 6%.

4.2 Case study II

Reference [31] focuses on 750 V DC metro, Tehran, Iran, a gas pipeline parallel to the metro with a traversal distance of less than 10 m that is buried at a depth of 1.2 m underground. Not the entire rail path is placed underground as some stations are on the surface. The voltage of the rail compared to the infinite ground was measured. Voltage oscillations of the gas pipe are due to the stray current of metro dynamics. The measurement was performed using a voltmeter with high internal resistance. The value of the voltage [copper sulphate electrode (CSE)] is measured via a comparison with a reference electrode (such as the \( \text{CuSO}_4 \) electrode buried 10 cm higher than the gas pipe). The rest of the data can be found in [31]. Pipe voltage measurements were made in seconds intervals for a duration of 5 min (however, the horizontal axis of Figure 5 shows 15 min intervals). The experiment results can be compared with modelling results.
TABLE 2 Different mesh grid designs

| Description | Type of Design | Shape of Connection |
|-------------|----------------|---------------------|
| Plan A      | Four separate metal conductors under each rails |                      |
| Plan B      | Two separate single layer mesh networks |                      |
| Plan C      | Separate multilayer mesh network |                      |
| Plan D      | Interconnected multilayer mesh network |                      |

FIGURE 4 Potential test on pipe-soil, running rails, gas pipe, and test points

and those of the VDI method in Figure 6. According to this figure, the proposed method provides an acceptable accuracy in the calculation of voltage around the rail. The maximum error of the proposed method in comparison to the test results of ref. [31] is 5%.

5 | DISCUSSIONS AND SIMULATION RESULTS

The system under study has a length of 1 km and contains a train that can be extended. The current injected by the train at 0 m equals 4000 A and this current is collected by the substation at the end of the tunnel. The worst static case possible was analysed, that is when the stray current has its maximum value. The flow of 4,000 A from the running rails increases the potential difference between the rails and the ground, which in turn generates a stray current. Given the material of the rails having a longitudinal resistance of 50 Ωm/km, when the two parallel rails draw 4,000 A current, each rail draws 2,000 A and according to the longitudinal resistance of the rail therefore the potential difference between the beginning and end of each rail will be 100 V. For modelling the voltage of the beginning of the rail where the train is present, one can consider the

FIGURE 5 The values measured in [30], simulation with CDEGS software, and the proposed voltage distribution indices (VDI) method for voltage of the gas pipe compared to the infinite ground potential at different times (the upper and lower curves concern points P1 and P2, respectively)

FIGURE 6 Voltage values measured in [31] and obtained in simulation with CDEGS software and the proposed voltage distribution indices (VDI) method for the gas pipe compared to the voltage value of the reference electrode at different times
potential of +50 V and at the end of the train near the substation the potential is considered −50 V. Positive voltage indicates that the stray current leaves the conductor and consequently metal corrosion occurs, but at negative potential, the stray current is transferred from ground to rail. At a distance of 500 m from the train, the magnitude of the rail voltage will be 0 V. The rail-to-ground resistance is 100 Ω/km, thus the size of the rail-to-ground resistance for a length of 500 m will be 200 Ω. (The contact surface of the rail with the ground is actually the cross-sectional area of this resistor, so when the length of the rail is halved, the length of this resistor remains constant and its cross-sectional area is halved, so the size of the resistor is doubled.) The average voltage for the first 500 m near the train is 25 V (the average potential of the running rails over a 500 m length), which due to 200 Ω resistance, a stray current of 125 mA is produced, and the total stray current due to having two rails will be 250 mA. The modelling results in the following sections confirm the values obtained from manual calculations. The stray current collection grid under the rail receives these stray currents, and at the end of the tunnel, near the substation, the injected currents leave these collectors. The three-dimensional image of the net stray current entering and exiting the collector is shown in Figure 7. At a distance of 500 m from the train, that is in the midpoint of the rail where the injection current of the rails is zero, no stray current is exchanged between the soil and the collector grid (Figure 8). At this point, the stray current collection grid contains its highest current.

For a tunnel, copper shields, galvanised steel bars, and mesh grid can be used as a stray current collector with copper cable.

5.1 Simulation results with CDEGS

The proposed scheme is modelled in the CDEGS environment and the resistance between all the elements in the arrangement is obtained. According to the calculations in the previous section, it is known that each rail injects 125 mA stray current into zone 2. Therefore, there is a total 250 mA stray current, the distribution of which among the conductors installed under the rail needs to be specified. The longitudinal resistance between the rails and the ground is not the same all along the path. Because it is not possible to model discrete insulation in this software, the effect of this resistance is modelled as a resistive coating between the rails and the ground and, as it is necessary for conductors in the MALZ module to be located under the ground [22, 24], its equivalent is modelled using an outer perfect insulation layer to represent the exposure to the air. Table 3 shows the current distribution between model components.

| Description                                    | Current (mA) |
|------------------------------------------------|--------------|
| Total stray current rails                      | 250          |
| Stray current collected with collector system  | 207.739      |
| Stray current collected with mesh network      | 120.235      |
| Stray current collected with cable             | 87.504       |
| Stray current collected with ring of tunnel    | 0.264        |
| Total stray current reached the buried structures | 0.172       |

![Figure 7](image1.png) Net stray current entering and exiting the buried collectors

![Figure 8](image2.png) The amount of stray current left in the collector along the track

![Figure 9](image3.png) Stray current collection by structures buried in different soil types
The stray current distribution between components in different locations (mA)

| Description                        | 100 mm | 200 mm | 300 mm |
|------------------------------------|--------|--------|--------|
| Total stray current rails          | 250    | 250    | 250    |
| Stray current collected with collector system | 213.682 | 209.957 | 207.739 |
| Stray current collected with mesh network | 125.451 | 122.143 | 120.235 |
| Stray current collected with cable | 88.231 | 87.814 | 87.504 |
| Stray current collected with ring of tunnel | 0.237 | 0.251 | 0.264 |
| Total stray current reached the buried structures | 0.073 | 0.126 | 0.172 |

### Table 5: Comparison of the VDI method results with CDEGS software output (mA)

| Solution Method                        | VDI method | CDEGS |
|----------------------------------------|------------|-------|
| Total stray current rails               | 250        | 250   |
| Stray current collected with collector system | 212.163 | 207.739 |
| Stray current collected with mesh network | 123.849 | 120.235 |
| Stray current collected with cable      | 88.314     | 87.504 |
| Stray current collected with ring of tunnel | 0.274 | 0.264 |
| Total stray current reached the buried structures | 0.164 | 0.172 |

Abbreviation: VDI, voltage distribution indices.

collection status of the conductors around the rails in the mesh grid design with copper cable.

In modelling, the worst type of soil, that is that with a high moisture content and a resistivity of 10 Ω.m, is considered. However, one of the solutions to confront stray current is to optimise the substrate soil and use a multilayer substrate with high resistance to prevent current leakage. Resistance of the soil and the substrate concrete can be increased up to 200 Ω.m. Figure 9 illustrates the effect of soil type on stray current.

The obtained results are shown for the case where the steel mesh grid distance from the running rails is 30 cm. The distribution of the current between the metal components of the tunnel at the closest collector–rail distances is shown in Table 4. It is predictable that the shorter the collector conductor distance from the rails, the greater the amount of current collected by it, and in fact the current reaching the adjacent structure will be lower. Nonetheless, the reinforcement aspect should also be taken into account and the metal substrate must bear high weight and pressure.

The results provided in Tables 3–5 demonstrate that the second design of the stray current collection system is capable of collecting more than 82% of the stray currents propagated in the ground and less than 0.2 mA of the current reaches the adjacent structure’s foundation. Depending on the service life and the investment cost, the layout of the system may undergo changes, such as the arrangement of four separate steel bars with either a cable under each rail, or a copper shield with a 20 cm width under each rail can be used, or the number of bars can be changed or a multi-layer mesh system employed under the rails. The results of these various arrangements can be compared in Figure 10.

### Figure 10: State of stray current collection by the buried structure in different stray current collection systems

I. 4 steel rods without copper cable  
II. 4 steel rods + copper cable  
III. 6 steel rods + copper cable  
IV. Copper shielded without copper cable  
V. Mesh network  
VI. Mesh network + copper cable

If two rails are in parallel, the current in one rail will affect the other rail, and at any given moment at different points in the soil the effects of both currents can be experienced. By modelling the circuit, calculating the potential level of each point, and examining the moment-to-moment motion of the trains, the sum of these two currents will be available at any given moment. Thus, the collector sizing can be calculated separately under each rail according to the worst-case plan. In case the adjacent collectors are connected to each other within 100 m intervals, part of the current collected by each system is transferred to adjacent conductors. This current flows along the path parallel to the return current in adjacent conductors and returns to the rail at the end of the track near the negative busbar and transfers to the traction substation.

#### 5.2 Results of the VDI method

Using the equations described in Section 3, the voltages of all conductors and reinforcement of the foundations are investigated and the amount of stray current reaching them through the running rails is available. The voltage level and current collected by the collectors can also be calculated. Considering
the transversal distance near the two rails, it is necessary to place the longitudinal collector along the path of the entire rail because these conductors, similarly to cables, play an important role in transferring current to the traction substation in addition to absorbing the current. In the case of transversal conductors of the mesh that are perpendicular to the direction of the rails, the density of the conductors can be changed depending on the amount of stray current of the line and the sensitivity of the structures around the rails. Using a genetic algorithm (GA) and considering the stray current collection rate of 75% by collectors, the objectives will be minimising the cost function by considering steel bar cost (cost of horizontal conductors; CCond), construction labour cost (install and backfill conductors and rods; Crench), and connection cost (Cconnect). Figure 11 shows the amount of stray current collected by each of the four proposals and the cost of implementing each plan for the entire route.

Considering the two objectives of maximising the stray current collection as well as reducing installation costs and noting that plan A may undergo long-term deformation under running rails, a penalty coefficient for this cost function can be assumed so that the design will not differ much in comparison to other plans. This design imposes less cost due to the absence of transversal conductors. Considering this problem for plan A, it can be seen that plan B gives the best solution to the objective, and plans C, A, and D, respectively, fall into lower ranks. Plans C and D, despite absorbing more of the stray current in the soil, have no economic justification because of imposing additional cost with respect to plan B. Plan A is more economical but provides less current collection than the other plans and cannot meet the main objective. A comparison of the results obtained by the VDI method with the simulation results given by CDEGS software is summarised in Table 5.

The validation carried out in Table 5 demonstrates that the difference between the results of the proposed method and the simulation results is less than 5%. Regarding the fact that the proposed method is simpler and more accessible, analytical results and model results of both verify that the use of the collector arrangement of plan B often absorbs the flow of stray current into the soil and prevents corrosion of the buried structure around the rails, as well as providing the economical cost compared to other plans.

6 | CONCLUSION

With regard to all the available methods for evaluating and controlling stray current given in the literature, various arrangements for primary protection for adjacent structures and buried pipes are presented herein. Collectors installed beneath the metro rails absorb most of the stray currents flowing from the running rails into the track-bed soil. Reinforcing the substrate by applying high-resistive layers reduces the amount of current flowing to other surrounding structures. The presence of steel mesh cable as a stray current collector in the metro tunnel creates an excellent path for stray current flow and reaches the negative busbar of the traction substation located at the end of the track. By applying the VDI method, the voltage of every point on the buried conductor and current collected by each collector are obtained simpler and faster than with the modelling methods. As the probability of fault in the practical test for calculating the reference electrode voltage under the ground is high, the proposed method, whose accuracy is within the acceptable range, can be an appropriate alternative to experimental methods. Considering two objectives of absorbing the stray current by collectors and reducing the installation cost of collectors, the efficiency of the proposed method to determine the arrangement of collectors was demonstrated. The results obtained from the proposed method are similar to the simulation results provided by the software and EN standards. The introduced models can absorb a large amount of stray current in the soil and reduce the probability of corrosion of the buried structure around the rail to nearly zero.

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