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Review

Stray Current Distributing Model in the Subway System: A review and outlook

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Subway system has been widely applied to the urban rail transit system. However, many negative impacts such as the electrochemical corrosion on the subway track and third-party buried metallic infrastructure caused by the stray current, has gradually appeared. This kind of electrochemical corrosion will cause a great threat on buried metallic structure and personal safety. Numerous scholars studied this from various aspects, in which the stray current model is extensively used as an effective means of analysis. In this paper, the existing stray current distributing model is firstly reviewed and analyzed. Secondly, rail potential problem analyzed by means of the stray current distributing model is reviewed. Thirdly, stray current simulation methods are also presented and discussed based on the stray current distributing model. At last, the developing direction and trend of stray current distributing model in the future study is point out based on the content reviewed above.

Keywords: Stray current; Electrochemical corrosion; Numerical calculation model; Simulation model; Subway system

1. INTRODUCTION

Due to the limitation of construction and maintenance costs, the running rail is often used as traction loop in subway dc traction system. The rail has limited conductivity and insulation is not completely over the ground, so a part of the traction current will flow into the earth throughout the running rail and return back to the traction substation by the earth diversion, instead of returning to the traction substation along the rail directly [1]. This kind of current, which flows into the earth through the rail, is called the stray current. Stray current is an unstable physical quantity. Two reasons mainly lead to the cause of it. First reason is the current leakage. It's mainly caused by the factor such as the insulation problems or contact between rail and insulating pad. Because current leakage point exists along the rail, thus the current flows through the running rail on the earth, then the separation phenomenon between cationic and electronic in the metal of the electrolyte is generated. In this way, buried metal like oil pipeline is corroded. Second reason is the electric potential gradient. Metal structure is put in the electric field, the potential distribution of which is quite heterogeneous. Due to the reason that the potential gradient is existed in the electric field, which produces electric field force to the free electrons in a metal. Thus, the free electrons move out of the cationic in a fixed direction, which eventually leads to the corrosion of buried metal.

The stray current can be divided into two parts, as shown in Fig. 1. The stray current which flows into the stray current control mat (SCCM) is referred to as the primary stray current, some of it is collected by the SCCM instead of continuing to leak to the earth. Accordingly, the stray current which leaks into the earth instead of being collected by the SCCM is referred to as the secondary stray current.

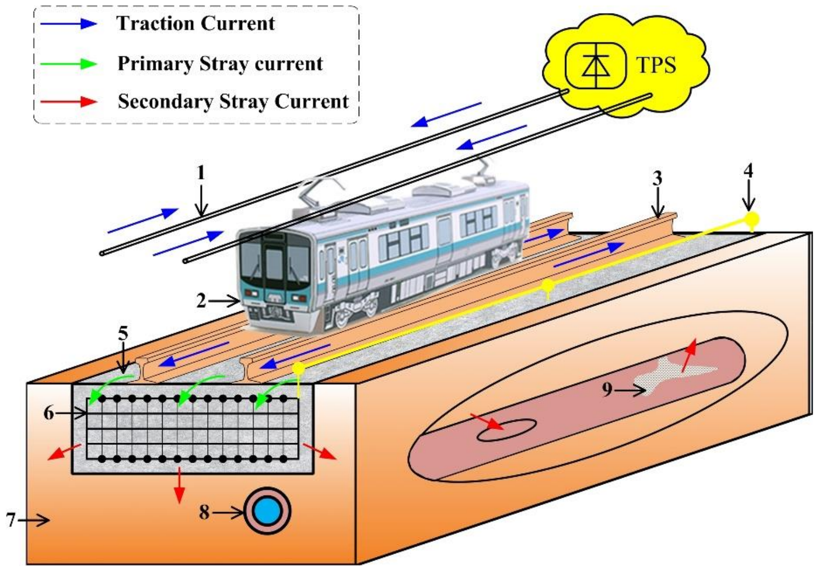

Figure 1. Three-dimensional stray current profile in the subway system.
1——Catenary; 2——Train; 3——Rails; 4——Stray Current Collector Cable;
5——Ballast Bed; 6——Stray Current Control Mat; 7——Surrounding Soil;
8——Buried Pipe; 9——Anode Zone

Stray current has a corrosive effect on the reinforced concrete through hydrogenation and the accumulation of corrosion products. In the cathodic area, if the cathode induces hydrogen evolution and the hydrogen cannot escape from the concrete, the isostatic pressure is formed, which will casue the rebar to be disengaged from the concrete. In the anodic area, the rebar is anodized and corroded. Then the accumulation of corrosion products will squeeze the concrete by mechanical action and crack it. The corrosive effect of stray current on the reinforced concrete is shown in Fig. 2.

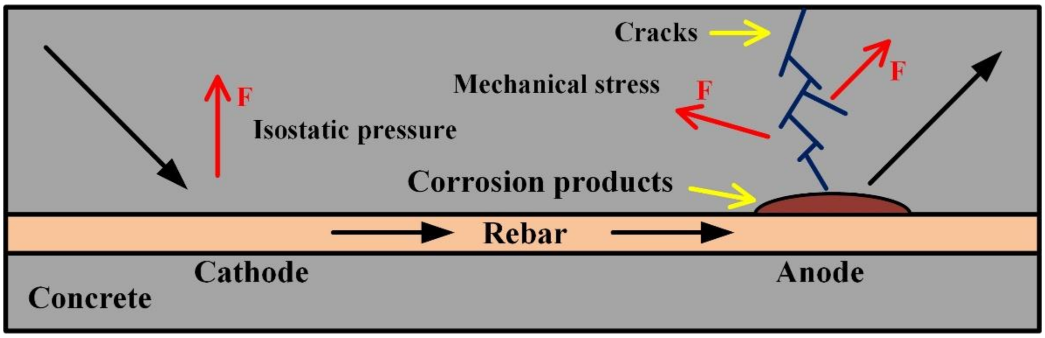

Figure 2. The corrosive effect of stray current on the reinforced concrete.

The buried pipeline in the subway system mainly includes water supply lines, oil pipelines, steam pipelines, etc. The buried pipeline outside the subway system mainly covers public utilities pipelines like gas pipelines, oil pipelines, water pipes, and a variety of cable pipelines. According to the related investgation, the stray current corrosion problem exists in these pipelines, and the pitting occurred on some iron piepelines within a few years or even a few months [2,3]. The corrosive effect of stray current on the buried metallic pipe is shown in Fig. 3.

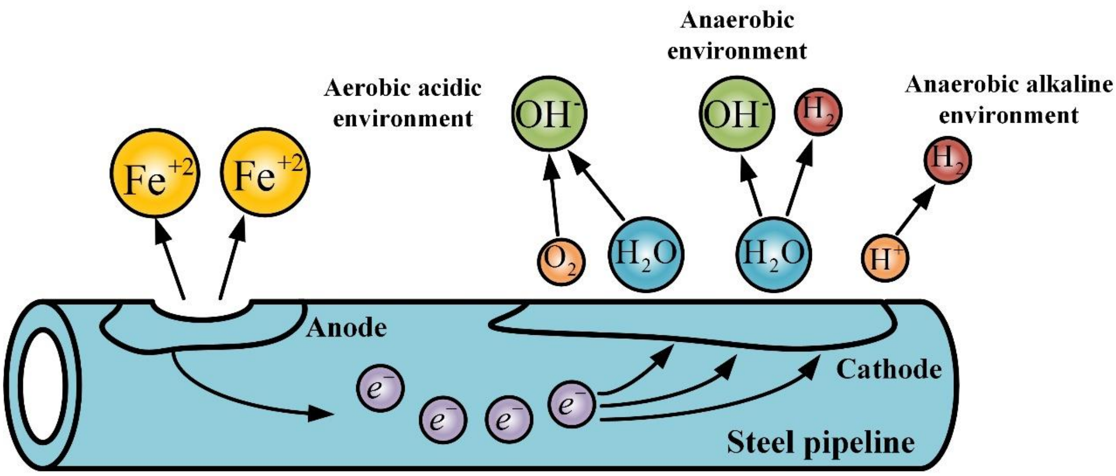

Figure 3. The corrosive effect of stray current on the buried metallic pipe

The cathodic area is produced when the secondary stray current flows into the buried metal pipeline, then the reduction reaction is occurred in the cathodic area. Due to the difference of the reduction reaction environment, the specific reaction equation could be different:

Hydrogen evolution corrosion(Cathode):

$4H{+}{+}4e^{-}{=}2H_2\uparrow$ (Anaerobic alkaline environment)

$4H2O{+}4e^{-}{=}4OH{-}{+}2H_2\uparrow$ (Anaerobic environment)

Oxygen absorption corrosion(Anode):

$O_2{+}2H_2O{+}4e{-}{=}4OH^{-}$ (Aerobic acidic environment)

The pipeline potential will reduce, when reduction reaction occurs. The pipeline in cathode zone is not affected generally, but if the potential value in cathode zone is too large, the precipitation of hydrogen on the pipeline surface is generated, which will cause anticorrosive coating fall off from the buried pipeline.

The anode zone is produced when the secondary stray current flows into the buried metal pipeline, then the reduction reaction is occurred in the anodic area:

$Fe=Fe_2+2e^-$

The pipeline potential will rise, when oxidation reaction occurs. The metal is oxidized to produce metal ions into the electrolyte(soil). Then the metal corrosion is produced due to the loss of metal ions. Not only for the metal pipeline, the stray current will also accelerate the corrosion rate of a variety of metal structures such as the running rail, its accessories, reinforce concrete, etc [4].

The electrolytic phenomenon is produced on the underground metal pipelines and reinforced concrete near the rail line because of the secondary stray current. According to the Faraday's law of electrolysis, for every amp stray current through the underground steel metal facilities, 9.1kg metal is corroded in a year [5]. Data provided by the Beijing subway shows that the stray current flowing into the earth is more than 100A. Otherwise, there are more than 5~32 ampere of stray current between the two new metro transformer substations in Washington, USA [1]. Therefore, the secondary stray current is the emphasis of stray current corrosion calculation and monitoring. Meanwhile, due to the influence of the stray current and track self-impedance, the electrical potential difference is generated between the running rail and the earth, which will endanger personal safety and corrode subway structures and buried metallic pipelines in when serious. Specifically, the electrochemical corrosion will not only reduce the reinforcement concrete structure in the subway system, but also shorten the life of metal pipelines, which may even lead to catastrophic consequences. In the laboratory environment, the corrosion of the specimen cut from HRB500 rebar and the Q215 pipe by simulated stray current is shown in Fig. 4.

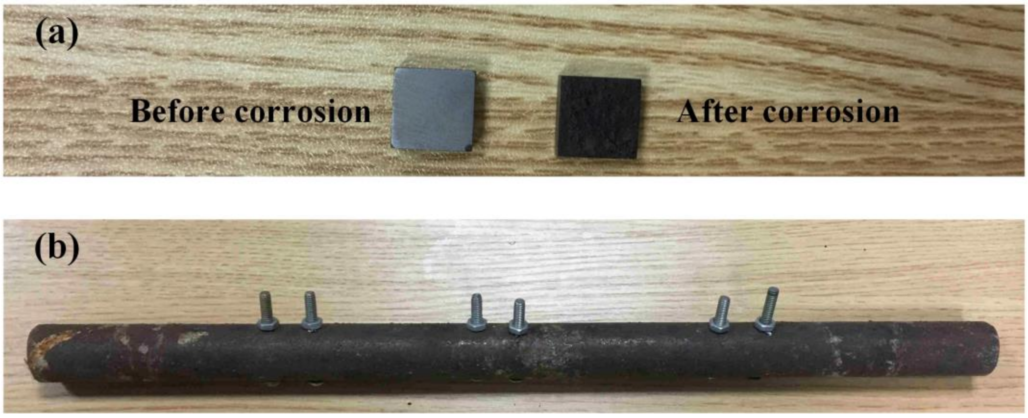

Figure 4. (a) The corrosion of metal specimen cut from HRB500 rebar and (b) Q215 pipe by simulated stray current.

In order that the threat of personal safety and corrosion on buried metal structure generated by the stray current should be avoided in the subway system, stray current and rail potential control should be taken accordingly. CJJ 49-92 [6], GB/T 19285-2003 [7], EN 50122-1 [8] and EN 50122-2 [9] provide corresponding standard for stray current assessment and acceptance. The most fundamental method to prevent stray current corrosion is to reduce the leakage of stray current [10]. Due to the complexity of the stray current, it is diffcult to carry out the direct measurement. The stray current distributing model is an effective means of analysis to study the electrochemeical caused by stray current, and to furtherly prevent it. The analysis of stray current distribution regularity is the basement of stray current corrosion prevention, and the stray current distribution model is the effective methods to study the stray current distribution regularity. In this paper, a critical review of stray current distributing model will be presented and discussed from the numerical calculation model and the analytical model. The rail potential problem related to stray current distributing model will also be presented and discussed.

2. STRAY CURRENT DISTRIBUTING MODEL IN THE SUBWAY

Stray current distributing in the subway system is a complex problem about electric current field, which is connected with tunnel structure, tunnel space geometry size and relative position between the locomotives. To prevent the stray current corrosion, the influencing factor of the stray current distributing is need to be analyzed firstly, then the theoretical model between stray current and influencing factors. The stray current distributing regularity is obtained finally, which offers a theoretical reference for establishing the protecting system. The stray current distributing model is simplified mainly from two aspects: (1) the space problem simplification for the plane problem; (2) the current electric field problem simplified for the circuit problem of distribution parameters. In the study of stray current distributing model, when faced with the situation that multi-locomotive and several power supply substations is concerned, common method is to simplify it to single train with single substation (unilateral power supply) or single train with double substations (bilateral power supply).

Overall, a variety of methods is used to analyze stray current distribution, including: resistive-type network model [5], finite cell model [11], Π type finite cell model [12], earth return circuit model [13], lumped parameter model [14], equivalent semi-cylinder layer model [15], hemispherical electrode model based on electric field [16,17], longitudinal sectioning model (A transversal equivalent circuit is developed based on a 3-D soil modeling for each section) [18], model based on the Tableau method [19]. The resistive-type model is shown in Fig. 5. In the model, the locomotive is often simplified as an ideal current source, the static model is referred to as the fixed locomotive traction current in time domain, the dynamic model is referred to as the locomotive position changing with distance and time. In terms of model solution method, methods like algebraic computation, numerical solving method, and software simulation is included in view of the complexity of different models.

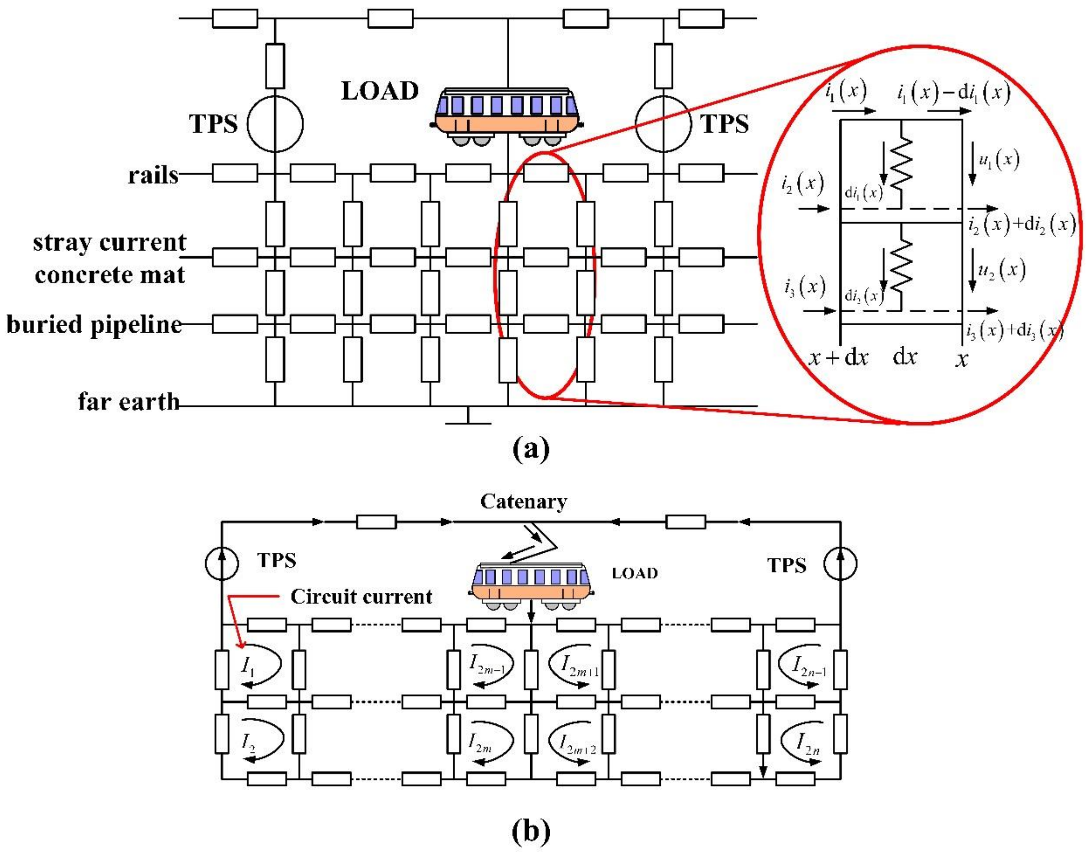

Figure 5. Resistive-type network model
(a) Continuous stray current distributing model; (b) Discrete stray current distributing model.

3. TRADITIONAL NUMERICAL CALCULATION MODEL

Perhaps the first publication that provides detailed analysis method to assess stray current is presented by McCollum *et al* [20, 21]. The paper provides a solution method for calculating the stray current under the circumstances of grounded or un-grounded dc-electrified railways, and also put forward that the leakage factor is used to control the size of stray current. Specifically, it is necessary for fuether stray current mitigation to keep the leakage factor as low as possible.

Schwalm and Scandor detailed such a view that running rails are generally not insulated from the earth so that part of the return current flows into the earth and make use of any metallic underground path in the vicinity that provides conductivity [22]. Schaffer analyzed the effect of running rail and power system design on stray current, and stated that no stray current collection system will be needed if running rail insulation and power system design can make the stray current in a safe range [23].

Furtherly, Baeckman and Hu derived formulation of leakage current in the running rail during the locomotive operation, and analyzed three kinds of return current including running rail-soil, running rail-pipeline, and the grounding of dc supply. Ultimately, analytical model of rail current and rail potential is presented [24, 25].

On the basis of the uniform distribution of insulation between rail and earth, Beackman built up a continuous model with two variables——rail longitudinal resistance and rail-to-earth transition resistance. Ardizzon *et al* introduced the equivalent input impedance as the boundary condition when building up the model of rail current and potential, also the specific calculation formulation is presented [26].

Yu and Goodman assumed that the rail longitudinal resistance and the rail-to-earth transition resistance is uniformly distributed during their study process, but in reality, these parameters will be affected by the number of rail, the distribution of soil resistivity, and the ballasted condition [11]. In consideration of the limitations of such model, Yu and Goodman splited the running rail into finite element along the longitudinal direction and established the relationship among node voltage, current vectors, and admittance matrix according to the principle of the node current voltage balance between units [27], as shown in Fig. 6. The node voltage matrix equations with lumped parameter are built using the variable parameters of the rail voltage and rail-to-earth resistance:

$$[G][V]=[I_s] \tag{1}$$

where G is conductance matrix; V is voltage vector; Is is injection current vector.

The accuracy of finite cell modelling depends on three aspects: the termination resistances, the number of cells used, and the line length. With the help of this model, the distribution of stray current can be calculated systematically in the case of changing parameters like rail potential and rail-to-earth resistance.

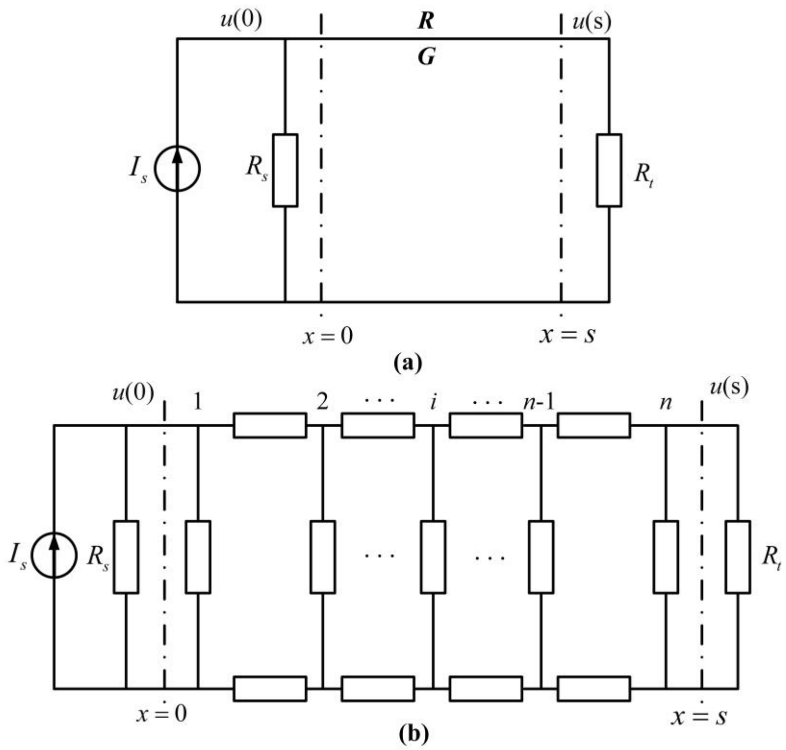

Figure 6. Finite cell model of stray current (a) A section of transmission line under shunt energization; (b) Finite cell model of the transmission line.

Based on this model, two parameters concerning the excessive rail potential due to stray currents from dc electric railway were proposed by Yu and Goodman, which are the total stray current (as a function of time) and the gross electric charge leaked from the railway during a period of time. In this paper, the calculation of these two parameters were calculated and the corresponding simulation model is established, which includes transmission line model and multi-train simulator and the integrated model; by using these model, rail potential, leakage current densities, total stray current, and maximum rail potential were simulated. It turned out that: the stray current leakage can be reduced by the rise of rail-to-earth resistance effectively; the depot acts a low resistance ground, connection of the depot to the track results in higher leakage current; for a total stray current, the ungrounded scheme results in the lowest total stray current (TSC), the direct-ground scheme results in the highest TSC; a lower rail-to-earth resistance increases leakage current significantly [11]. Based on the model proposed by Yu and Goodman, Case built up a Π type model in which the running rail resistance was divided into a series of short sections or "cells" in the [12], as shown in Fig. 7. For each cell, the basic parameter of track is represented by a longitudinal resistance (δRT) and a rail-to-earth resistance (δRE). The node analysis was used to calculate the node voltage and current in four traction substation segments. The total stray current was found by adding up all these currents whose direction is into the earth [12]. Case analyzed the advantages and disadvantages of different grounding scheme combining EN50122-2, but it is not analyzed specifically in the stray current distributing model. Cai *et al* modeled multi-ladder and multi-branched dc traction power system based on lumped parameters, then the node voltage, branch current, rail potential, and the total stray current in the reflux system was analyzed, but the effect of soil resistivity on the stray current distributing was not analyzed [28,29].

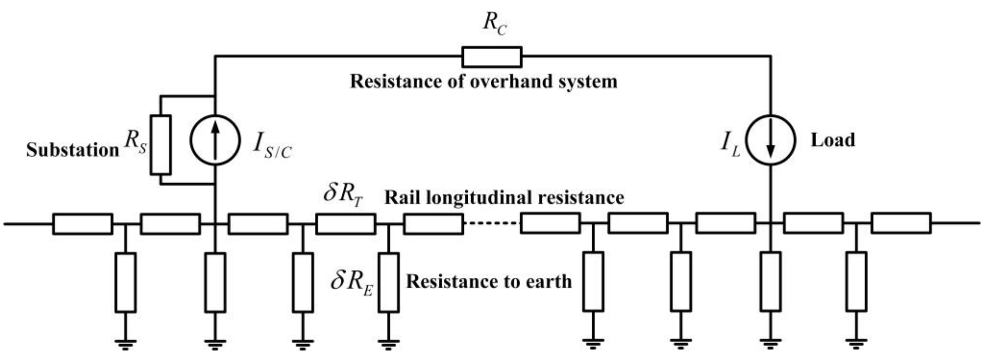

Figure 7. Equivalent circuit representation using track "cells".

Traditional stray current distributing model is mainly based on the resistor network to analyze the stray current static distribution, in which the actual dc traction system is abstracted to resistor network model. Traditional stray current has been applied to many existing stray current monitoring system. As aforementioned, many simplification methods are used for the traditional model to make the solution easier, and the model expression is more straightforward. However, due to the simplification, the engineering environment of the traditional model is relatively ideal, not considering the distribution of stray current in special cases such as soil resistivity changing, pipe coating damage, and rail insulation damage etc.

4. NOVEL NUMERICAL CALCULATION MODEL

When stray current distributing model is mathematically derived by traditional circuit theory, many assumptions are made. Parameters like longitudinal resistance, rail-to-SCCM transition resistance, soil resistivity, SCCM resistance, and SCCM-to-structural steel transition resistance is all uniformly distributed; feeder circuit impedance is ignored, etc. Because of the limitations of the above assumptions, a lot of difficulties is faced in the process of practical analysis, and problem like great difference between the analytical model and the actual working condition still exists. Therefore, many scholars tried to analyze stray current distributing model from the perspective of other theoretical model, or to adjoin actual working condition by setting new boundary conditions for existing theoretical model [13-19,30-39].

4.1 Stray current distributing model based on new basic theory

Based on the assumption that the resistance of the overhead contact system to ground is very high and there is no coupling between the positive circuit and earth, Pham and Thomas built up the basic analytical model of stray current distributing in the running rail-soil-reflux system with the boundary condition that damage is existed at the insulation between running rail and the earth, assuming the ideal condition with uniformly distributed rail-to-earth resistances. In this model, the rail-to-earth resistance was lumped and concentrated at an equivalent hemispherical electrode, then the relationship between rail potential and stray current in the vicinity of the running rail was derived. The potential gradient was calculated using field theory generated due to flow of rail current finally, as shown in Fig. 8.

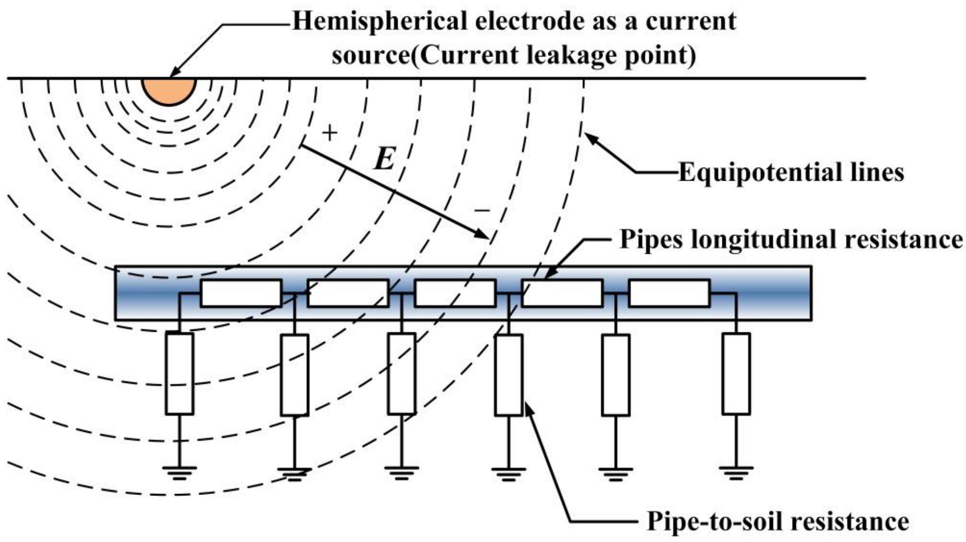

Figure 8. Earth potential gradient model.

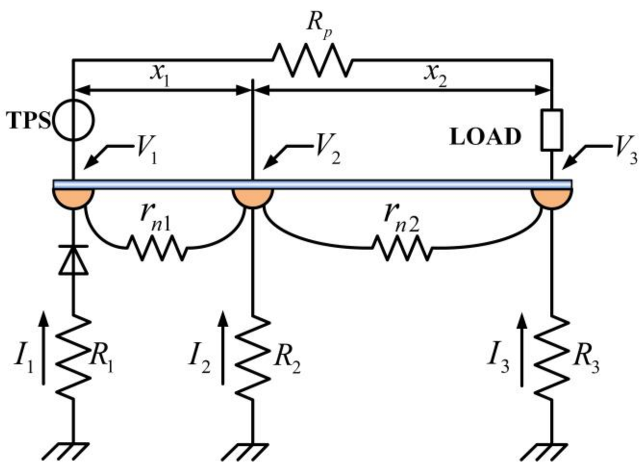

Figure 9. Basic stray current model using spherical electrodes.

Based on this model, the method to analyze the distribution of underground electric field using hemispherical electrode and to calculate the corrosion current which flow through the buried pipeline. As shown in Fig. 9, it turned out that the flow of current between two grounded electrodes is affected by three factors: the potential to distant earth of each point, the resistivity of soil, and the effective size of each electrode [30]. Pham *et al* proposed hemispherical electrode model to calculate the stray current for the first time, stray current distributing is analyzed from the view of current leakage point using the model mentioned above which is quite different from the resistor network model.

Smulders *et al* used half spherical earth electrode to represent a conductor in contact with soil within a certain range, and proposed a 3-D system of stray current distributing considering the following factors [18]. In such a system, resistor network model is divided into several transversal sections in longitudinal sections, in which the admittance matrix is built on. And also the coupling effect between longitudinal and transversal sections, coupling effect among transversal sections was considered. However, this system is still based on the resistor network, limitations are existed.

Pang *et al* employed corrosion as an intuitive criterion to evaluate the damaging degree of stray current to buried metal, as shown in Fig. 10. With a constant trend distributing trend of stray current underground, hemispherical electrode are used to obtain the electric field distributing, then the corrosion current was solved flowing through the buried metal, thus the corrosive quantity of buried pipeline was calculated furtherly. When the train passes through the whole power supply range, corrosive quantity of a certain point on the buried pipeline is:

$$W_P = K\int_0^t \int_0^L I_P \mathrm{d}l\mathrm{d}t \quad [16] \tag{2}$$

Where t is the time required of a train passing through a certain distance dl on the power supply range, L is the total length of the power supply range, Ip is the corrosion current of a certain point on the buried pipeline, K is the proportional constant. The study of Pang Yuan-bing *et al* is the further development of metro stray current based on electric field, in which the change from single electrode to multi electrode is the expansion to the model proposed by Pham and Thomas. Shen *et al* analyzed the stray current distribution under non-uniformly transition resistance in subway and discussed the actual problem caused by stray currents in specific subway engineering, which provides the theory basis for exploring the actual distribution of stray current [17].

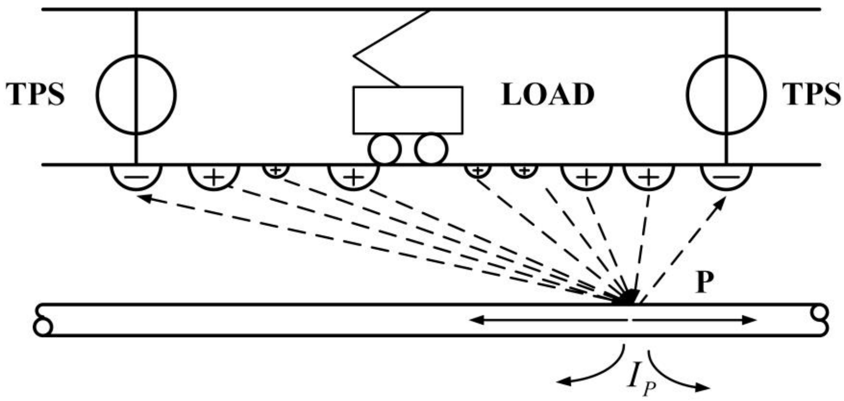

Figure 10. Stray current electric field model.

Cao proposed the stray current distributing model based on induced electric field theory, as shown in Fig. 11. When the steady current flow through the conductor with uniform thickness, there will be a surface charge on the conductor surface. Thus the potential gradient is formed within the conductor. In this way, the inductive electric field is generated by surface charge within the conductor, which will lead to the existence of the potential gradient in the external environment. Finally the stray current is produced [31]. Verified by the experiment, the model calculation results were in good agreement with the experiment results.

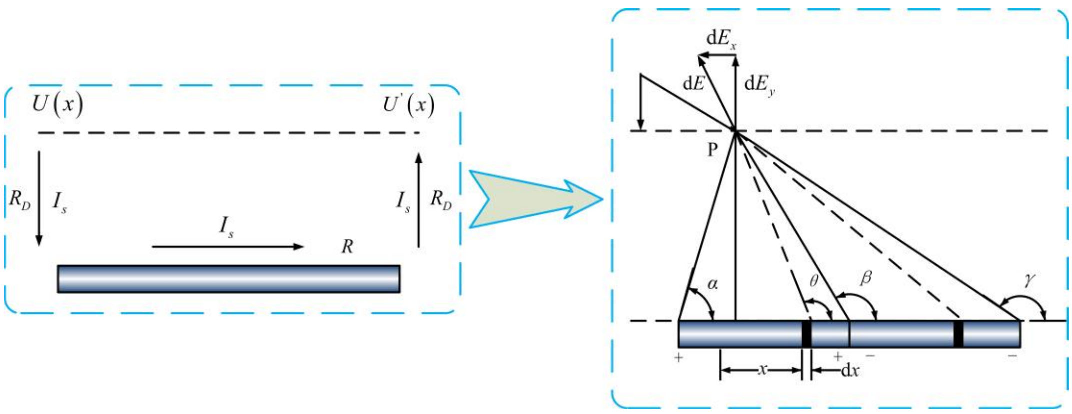

Figure 11. Schematic diagram of inducted electric field from the electrify conductor.

Based on the hemispherical earth electrode model, Li *et al* proposed a mathematical model of stray current under the circumstance of rail-to-earth insulation defect, and analyzed the stray current distributing under rail-to-earth insulation well and defect. It turned out that when rail insulation local damage occurs, the smaller the grounding electrode resistance is, the larger leakage current produces and the maximum rail potential is [32]. Therefore, it is especially important for keeping the transition resistance at a higher value by making the running rail clean, dry, and having good insulation with

SCCM in the daily maintenance.Du *et al* proposed a unified chain model of a DC traction power system to simulate the distribution of rail potential and stray current. The result shows that over zone feeding widely exists in DC traction power system, and that the rail potential and stray current can be both reduced effectively by preventing the over zone feeding of traction current.

4.2 Development of stray current distributing model based on resistor network

Ogunsola *et al* proposed the stray current distributing model in the cases of buried pipeline coating defect using resistor network. The formula for the resistance to ground of a long buried horizontal cylinder and the total spread resistance of a coating holiday including many parameters like coating thickness, coating defects, current flowing in the concrete mat and voltage impressed on the pipe as a function of vehicle position is emphatically analyzed [33]. Ogunsola *et al* described the implementation of an integrated model for the assessment of stray current for a dc-electrified railway, in which factors such as the train characteristics, time tabling, headway, multiple train movement, etc., were considered [34]. And also the stray current magnitude and the overall performance of the stray current collection system in the worst cases are assessed. Fichera *et al* evaluated stray current from dc-electrified railway with lumped parameter. This model was used toghther with both a uniform model and a multi-layer model to demonstrate the difference in stray current distributing [14]. Fichera *et al* compared distributed and lumped parameters stray current models, which are in general agreement [35]. Depending on this model, Mariscotti *et al* put forward the method to mitigate the electromagnetic interference generated by stray current from the dc-electrified railway system. It turned out that the control of the current flowing in the overall circuit is essential when stray current leaks from the running rail to the earth [36]. Therefore, proper design of constituent components is especially needed. Furtherly, Mariscotti analyzed the important components of reflux system: the running rail longitudinal resistance, the resistance between the rail and the stray current collection mat, stray current collection cable (SCCC) and proposed the corresponding optimization measures [36]. It turned out that the design provisions adopted for the Red Line of the Dubai Metro in compliance with EN 50122-2 effectively mitigate the stray currents and increase the overall EMC of the dc rail traction system.

According to a series of studies conducted by Ogunsola, Fichera, Mariscotti *et al*, the following important conclusions were drawn. It is estimated that the maximum stray current is only achieved for a short period of the time only when trains accelerate. The stray current intensity of multi-locomotive case is lower than the single-locomotive case as a result of the regenerative power exchange between locomotives. With a distributed or a local defect for viaduct insulation applied, the estimated stray current increases locally and the overall efficiency of the stray current collection system (SCCS) reduces. The estimated stray current amounts to a 10%–20% of the total collected stray current under the conditions of extreme insulation defects. Compared with the distributed model, the lumped model appears more suitable for handling scenarios under sharp parametric considerations, which may introduce abrupt changes in the current distribution. The research results of Ogunsola, Fichera and Mariscotti *et al* lays a theoretical foundation for establishing a composite model of stray current distributing under the influence of many factors.

Xu *et al* studied the effects of running mode on rail potential and stray current in dc-electrified railway system. Through a series of field test on the rail potential with different operating condition of the OVPD in Nanjing Metro Line 1, and the it was found that: when OVPD turned on at one side of the power supply range, 1/4 of the interval length of the rail potential would reduce at adjacent surrounding TSS around the OVPD, the rest 3/4 still maintain a high potential. It means that the rail potential at substation will reduce in the grounded system compared with the ungrounded system. Meanwhile, the field test of the rail potential and buried conductor potential for Nanjing Metro Line 1 was performed, positive and negative shifts of the potential were found in the acceleration and deceleration modes respectively. It was found that the running mode of the locomotive will have an impact on the rail potential and buried conductor potential. Furtherly, Xu *et al* proposed a stray current distributing model considering the running mode of the locomotive. In this model, the locomotive operation was divided into three modes: acceleration, constant-speed and deceleration, and the dynamic analysis of stray current distributing was realized in time domain, combining the subway traction calculation model and stray current distributing model. Different locomotive running mode at different locations leads to the changes of locomotive power, thus the traction current at different locations makes a difference. Then the dynamic mapping among running time, locomotive operation and stray current is established. The simulation result of dynamic model has the same trend with the field test results, whose correlation coefficient is 93%. It turned out that: in the acceleration and brake modes, the rail potential is relatively high; the rail potential is in the opposite direction during two modes [37].

Wang proposed a stray current distributing model based on multi-locomotive operation, in which the locomotive and traction substation are both taken as injection current sources that affect the underground structures to produce the stray current [38]. The micro-element algorithm is used to derive distributing model of various electric parameters based on single injection source. Then the multi-source model is superposed by a single source model. Finally, the multi-locomotive model is simulated to analyze the influencing factor.

Abandoning the traditional boundary conditions, Rodriguez *et al* proposed a rail potential distributing model to calculate the remote effects at any other point along the rail. The problem is defined as a function of the power demanded by the vehicle at each point $P(x)$, so the consumed current $I(x)$ is obtained by means of a power flow algorithm [39]. The essence of changes in the locomotive traction current $I(x)$, is the changes in the power $P(x)$ because of different running modes. With the equivalent tracntion circuit, a method for calculating instantaneous potential at any point along the rail is provided in this model as well. Whether in normal or fault condition, this study results have directive meaning for the design of railway traction tracks and substation spacing, which takes into account linear density limits like rail voltage and stray current.

In summary, many new boundary conditions are included in the stray current distributing model according to the literature discussed above, which breakthrough the limitation of the traditional distributing model. The relevant achievement promotes the improvement of stray current monitoring and drainage system. Unlike the traditional stray current distributing model, new models proposed by many scholars are more close to the actual working condition and the numerical calculation of stray current is more accurate, but such models are still limited to two-dimensional space. However, the existing model is mainly based on a uniform distribution of the rail-to-earth resistance parameter, which is far away from the actual engineering environment. Even if there is a series of hypothetical insulation damage points [16], it is diffcult to locate the damage point and determine the distribution of the rail-to-earth resistance in the case of insulation damage. Therefore, the parameter optimization in the stray current distribution model further research.

5. RAIL POTENTIAL AND STRAY CURRENT

According to the standard EN50122-1 [8] and EN50122-2 [9], the running rail should maintain a high insulation level, and stray current will cause obvious rail potential rise. Therefore, equipment damage is caused and the personal safety is threatened. Four kinds of grounding schemes: directly grounded scheme, ungrounded scheme, diode-grounded scheme, and thyristor-grounded scheme are mainly used in the subway system, as shown in Fig. 12. As for the further development of subway stray current study, it is found that the contradiction between the control of rail potential and stray current is an inevitable problem in practical engineering [40]. And also the relationship between the rail potential and earthing scheme has been researched during these years. Stray current distributing model is the basis of rail potential analysis and grounding method selection. The ground method of running rail has a great influence on the rail potential and stray current, so many scholars analyzed the rail potential by stray current distributing model combining the above factors, which provided a theoretical guidance for the choice of grounding method.

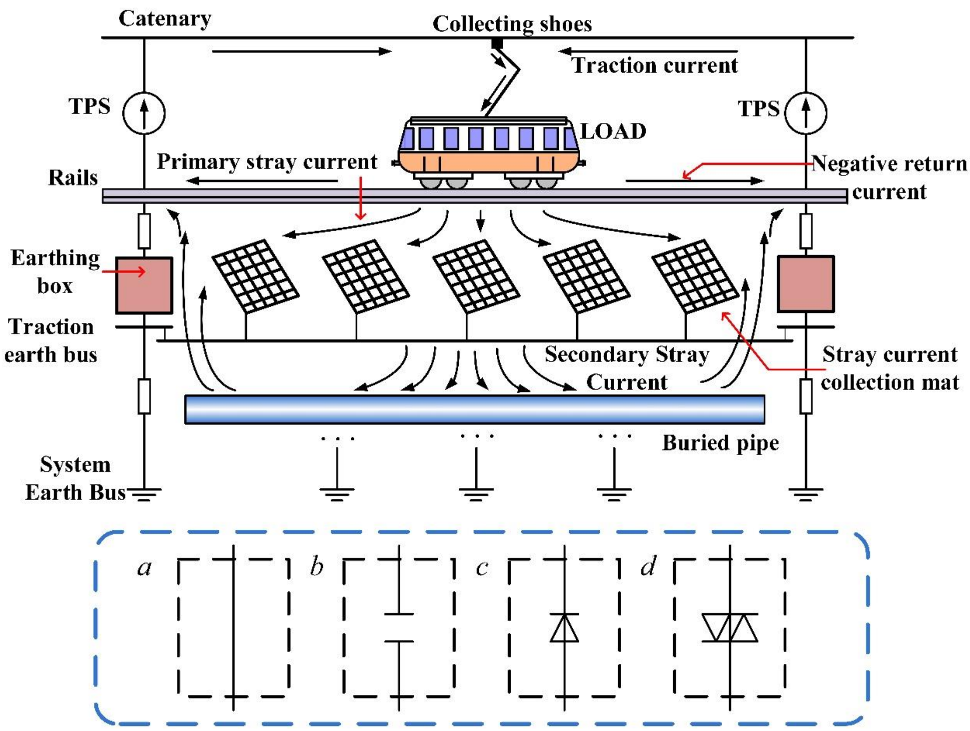

Figure 12. Stray current collection system along with 4 kinds of earthing strategies a: Directly grounding scheme; b: Ungrounded scheme; c: Diode-grounded scheme; d: Thyristor-grounded scheme

The overvoltage protection device (OVPD) is used to classify the different grounding schemes and maintain the rail potential within the allowable range of the standard. The schematic of OVPD is shown in Fig. 13. Yu J. G. studied 3 setting parameters of OVPD under the circumstances of floating earth, set 13 different specific cases, and calculated the overall maximum rail potential, the overall minimum rail potential, and the 1 hour's equivalent gross leakage charge. Meanwhile, the influence of the load in the cases of specific parameter setting and the grounding scheme on the rail potential along the section was analyzed. The stray current and rail potential at the single point was also demonstrated within the operation time. It turned out that the higher the voltage and current setting value, the shorter setting time, the lower the gross leakage charge; the floating earth scheme with rail potential control devices is the best choice [41]. The study of Yu J. G. lays a theoretical basis for the running rail grounding scheme selection and evaluation.

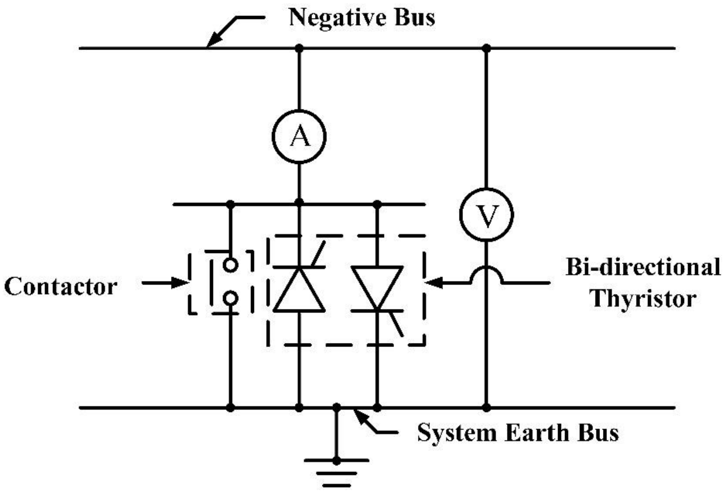

Figure 13. Schematic of a OVPD

Tzeng and Lee proposed a stray current distributing model with bilateral power supply in Taipei rapid transit systems, in which the power supply structure is divided into two substructures and the node boundary structures were used. The influencing factors like grounding scheme and cross-bonding running rails on the rail potential and stray current were analyzed. It turned out that: Although the rail potential can be reduced to about 20% in the literature, the stray current still cannot be significantly mitigated; if the insulation of running rails deteriorates, the aggregate stray current flowing through the TSS will slightly decrease, which is the closest to the deteriorated point,; from the perspective of potential control rail, ungrounded scheme is preferable to diode-grounded scheme [42]. The above study has the guiding significance for determining the rail-to-earth insulation damaging area. Both the EN50122-2 and VDE0150 stipulate that the maximum voltage between running rail and earth shall not be over than 0.1V, Lee proposed a model to study the maximum potential rise on the traction earth (TE) conductor caused by stray current in Taipei rail transit systems (TRTS), in which the calculation formula of rail potential is given. By calculating the maximum potential rise of different operation section in two models (A train start at a passenger station with and without TSS), the negative impact of stray current is evaluated combining with international standards, but the results were relatively conservative compared with the distributed parameter model [43]. Lee and Lu studied the stray current and rail potential distributing at a certain moment under different grounding scheme (floating grounded, solidly grounded and ungrounded) combining different locomotive operation mode. Furtherly, the advantages and disadvantages of three grounding schemes were analyzed. The control of rail potential and stray current is conflicting. A balance is needed to achieve between the two. Therefore, the subway system should choose the diode-grounded for effective control [44, 45].

Chen *et al* studied the influencing factor of rail potential and stray current distributing such as cross-transportation lines, rail maintenance and rail-to-earth resistance, grounding scheme, etc. Depending on the actual initial conditions, a series of field tests on electric field intensity, rail potential, rail-to-earth potential, and rail-to-earth resistance was conducted at Taipei Metro. Then the computational procedure to select substations with their drainage diodes turned on was designed for I_{stray} and V_{rail} evaluation. Aiming at the specific circumstances, the best connection form of drainage diodes was determined when the overall rail potential of several lines was minimum, and various factors affecting the rail potential were analyzed. It turned out that: the effect of I_{stray} collection by the stray current collection mat in the diode-grounded scheme presently adopted by Taipei Metro mainly depended on the number of substations having their drainage diodes turned on, both I_{stray} and V_{rail} can be reduced for the cases with three substations turned on in comparison with the cases having only one or two substations turned on; both I_{stray} and V_{rail} can also be reduced with longer headway or partly floating grounded instead of totally diode-grounded; the extension of the line length could worsen I_{stray} and V_{rail}. In order to ensure the isolation of two cross-junction lines, we can also effectively reduce the total amount of I_{stray} and the peak of V_{rail} by disconnecting the impedance bond at the tie line or at the cross-junction [46]. The experimental methods used by Chen *et al* in [46] provides reference significance for analyzing the influencing factor of rail potential and stray current, in which the complexity of actual lines is considered and the same parameter is repeatedly measured under different operation conditions.

Jamali *et al* set Tehran Metro Line 3 as the research object, the best grounding scheme is determined for Tehran Metro Line 3, by calculating stray current and rail potential combining multi-locomotive operation mode and locomotive running mode and doing a comparative analysis on cumulative charge under two different grounding schemes: floating grounded and diode-grounded. In dynamic simulations, the ungrounded scheme produces approximately 1.5 times less stray current in comparison with an equivalent diode-grounded scheme, and the diode-grounded scheme produces higher values of voltage at adjacent substations in comparison with the ungrounded scheme, which will deteriorate the safety. However, changing the diode direction in diode-earthed scheme effectively reduces stray current leakage [47]. Alamuti *et al* discussed four grounding schemes including thyristor grounded, diode grounded, floating and solidly grounded and their effects on the stray current distributing, pipeline corrosion and safety performance. Based on the simulation, a comparative study of safety and corrosive effects of the stray current, produced by various grounding schemes was presented. Furtherly, the traction current distributing when the locomotive is in the running operation along the whole line was obtained, and the cumulative corrosive charge, the rail potential distributing at some time and the flowing current at traction substation were calculated [48]. The related study of Jamali, Alamuti *et al* evaluates the subway grounding schemes from various aspects, which have practical significance for choosing specific grounding scheme weighing various factors: stray current, rail potential, personal safety, etc.

In summary, both the stray current and the rail potential in the safe protection of subway dc traction cannot be ignored; the former mainly corrodes the buried metal, which is harmful for engineering structure; the latter threatens the associated equipment and personal safety. But when the rail potential is too small, the stray current leakage amount increases, which will increase the possibility of buried pipeline being corroded. Besides, the too high rail potential will cause actual problem such as personal safety. Therefore, a balance between the two is needed considering a variety of factors. The study of rail potential uses an entry point of grounding scheme at substations, through the study of the grounding scheme of negative bus bar at substations. On the one hand, the stray current and rail potential is balances; on the other hand, the theoretical basis is provided for related lines to choose the best grounding scheme.

6. STRAY CURRENT SIMULATION

Different from the simplified analysis of the theoretical model, the simulation analysis is an effective tool to analyze the stray current distributing under complicated environment. Many scholars used these methods to do a lot of study. Stray current simulation analysis has a variety of ways, such as the finite element method (FEM), matlab simulation, CDEGS simulation, etc.

6.1 FEM

The FEM is a numerical technique to solve numerical boundary problems approximately, which can be used to calculate in situations that the boundary shape and geological conditions are complex and volatile, to handle various types of boundary conditions and to simulate the structure composed by a variety of materials. ANSYS is a large common finite element analysis software that is in the integration of structure, fluid, electric field, magnetic field, acoustic field and the coupling field analysis, in which the finite element analysis (FEA) can be used to do the simulation analysis for solving the real engineering problems. By means of the FEM, many research have been carried out on the stray current interference [15,50-54].

Hill *et al* studied the electromagnetic fields in dc traction systems using 3-dimensional finite-element analysis. The FEM was used to build up 2-d and 3-d model of the electromagnetic field. The rail is equivalent to half cylinder embed on the surface of the earth in 3-dimensional model, with multiple half cylindrical rings to multi-layers, as shown in Fig. 14. The constitutive relation of steady current was used to analyze longitudinal and vertical rail current density as a function of distance, and vertical and horizontal components of ground current density at point of current injection [15]. In the study of Hill *et al*, 2-d FEM was used to calculate the electric field density and potential gradient, and the equivalent transmission line parameters were derived; 3-dimensional FEM was used to analyze the current flow near the substations and the electromagnetic interference caused by dc traction. Both provide new thought for the application of FEM in the stray current distributing analysis.

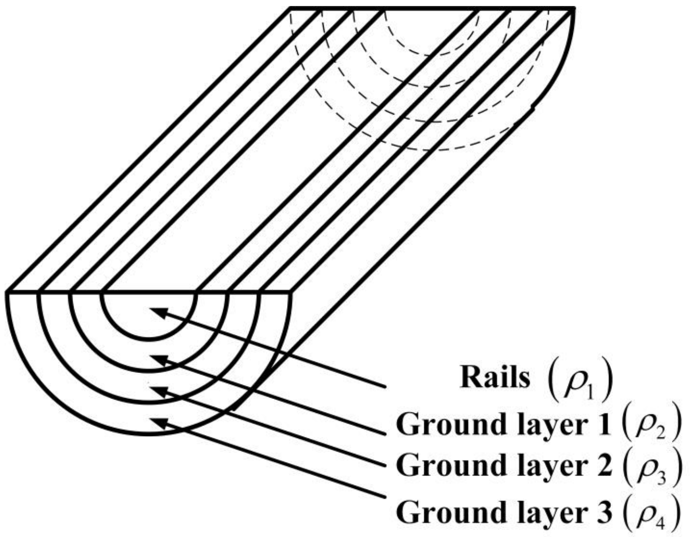

Figure 14. 3D DC traction system model.

Hu *et al* proposed a 3-dimensional mathematical model of stray current field from the anale of finite element method (FEM). It turned out that: the potential from the subway to the surrounding underground environment is nonlinear decreased. The farther away from subway tunnel, the lower the stray current intensity is. The influencing scope of stray current can be reduced effectively by increasing the resistance in the vicinity of the subway tunnel, which provides a basis for evaluating corrosion impact on the buried metal structure and determining the scope of stray current protection [50].

Brenna *et al* evaluated the possible corrosion effects on subway tunnel structures caused by surface tramway lines. Through the analysis of the equipotential surfaces and current field when average tramway track voltage equals to 8V corresponding to the hours of higher traffic, there are localized areas where the difference of potential between reinforcement bars and ground is greater than or close to the maximum value allowed by the standard EN50122-2. The root cause of corrosion is the potential difference, thus a significantly increased risk of anode corrosion exists her [51]. Furtherly, Dolara *et al* presented a solution for the above phenomenon——the equipotential connection between the reinforcement bars of the adjacent segments and rings. A deep FE analysis was conducted to compare the equipotential surface difference with and without the equipotential connection, which verified that the precautionary measure can limit the potential difference in the range of standard effectively and prevent the diffusion of anodic areas in reinforcement bars [52]. Futhermore, this will influence the design method for better environment compatibility. Brenna, Dolara *et al* reveals the mechanism of stray current corrosion in subway tunnel structure, and improves the protection design content of stray current corrosion for the newly-built subway tunnel.

Wang *et al* established 3-dimensional models of subway rectangular tunnels and subway shield tunnels, as shown in Fig. 15. Through the potential curves of stratified area in different directions, the simulation results demonstrate that, the maximum potential in the rectangular tunnel is bigger than that in the shield tunnel, also whose minimum potential is smaller than that in the shield tunnel [53]. Therefore, the amount of leakage stray current of rectangular tunnels is less than shield tunnels under the same geological condition. According to the standard VDE0150, the maximum allowed potential difference between affected metal structure and its surrounding medium is no more than 0.1V, which can be united with the electric potential contours to roughly determine the scope of stray current protection. Hu, Wang *et al* studied the stray current distributing in tunnel section, which offers a new method for stray current field numerical simulation research.

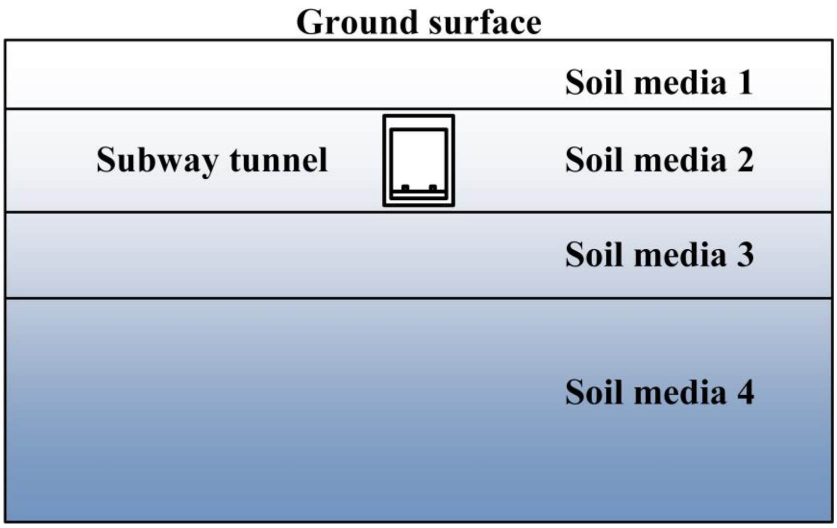

Figure 15. Sectional view of computional domain of subway stray current field (m).

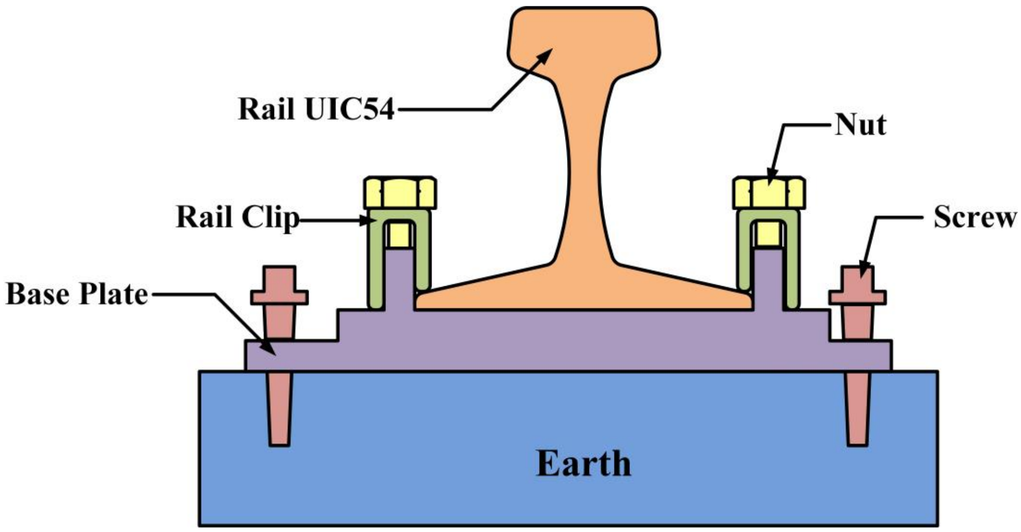

Figure 16. 3-D model of an insulated fastening system for rail UIC54.

Zaboli *et al* did stray current simulation using resistor network and FEM in matlab and ANSYS respectively. The primary and secondary stray current distribution in longitudinal and transversal directions was studied with stray current collection mats in uniform and horizontally two-layer models.

Then the stray current collection mats efficiencies for different soil models were calculated through FE analysis, as shown in Fig. 16. It turned out that the efficiency of SCCM is decreased with increased soil resistivity in uniform soil model. On the one hand, less resistivity of the upper layer leads to more efficiency; on the other hand, more resistivity of the lower layer leads to less resistivity in horizontally two-layer model. The SCCM can lead to collection of more than 85% of stray current which plays a major role in decrease of stray currents [54]. The study of Aydin Zaboli *et al* provides a novel idea for FEM method applied in stray current research.

In summary, the FEM offers the possibility to model stray current interference on 3D structures. The technological difficulty of stray current distributing FEM simulation is to simplify the actual subway dc traction reflux system effectively, on the basis of guaranteeing system characteristics. Meanwhile, the boundary condition for the actual FEM caculation on the 3D strcuture is particularly important. Nevertheless, the FEM is limited in the size of models that can be handled.

6.2 Simulink

Simulink provides an environment integration of dynamic system modeling, simulation and comprehensive analysis, which is one of the most important component of MATLAB. One of the SimPowerSystem is an advanced tool to model and simulate electric power and electronic system under the environment of Simulink. On the basis of the resistor network model, many scholars use the electrical network components and equipment to simulate the stray current distribution.

Seasonal variations leads to the change of moisture content and temperature, which influences soil resistivity. Ulteriorly, soil resistivity influences rectifier substation grounding grid resistance. Thus the stray current distribution is affected. For this factor, Cerman *et al* established a 2-dimensional resistor network model in Simulink. Based on the data of 6 seasonal variations of the grounding grid resistance from [55], the effect of grounding grid resistance changes due to different seasons on the stray current distribution is analyzed, with directly grounded model [56]. 2-D modeling in Simulink is a very useful tool to estimate approximate values, the accuracy of which is adequate.

Surface potential can be easily measured, but the measurement of potential far from the surface remains many problems such as low safety coefficient, hardly secured measurement equality, etc. The potential underground is an important factor of stray current near the rails, which can adversely affect cable lines near the rail. In the view of the above problem, Šprlark and Svoboda built a detailed two-layer model of stray current with locomotive and tram model in Simulink. Then the stray current at the railway rail and tramway rail was analyzed and compared with traction vehicles in operation. Potential in different ground layers under rails was also analyzed with two models. Although the vehicle model is different, both blocks include transformation station, trolley line, DC/DC and control block, block of traction motor, block of current of rails and subsystem of stray current, in which each layer was divided into several parts named “Qxy” and replaced by corresponding resistance [57]. Finally, polynomial fit was conducted according to the simulation results.Svoboda *et al* studied the potential in division of railway track with the same simulation method in [57]. Simulation shows that potential in the part C is a lower than that in the part B. Furthermore, the conclusion was drawn that the rail potential always reaches the highest values in the place where the electrical locomotive just passes [58]. Due to the simplification in the model, the effect of buried pipeline on the ground potential distribution was not considered in the study of Šprlark and Svoboda.

Jabbehdari and Mariscotti studied stray current distribution based on horizontally stratified multilayer soil structure with a constant resistivity for each layer, and proposed a 3-dimensional earth model based on the Tableau method. The numerical solution is achieved by means of a non-linear Least Square algorithm. Tableau analysis, a completely general method for the all linear circuits, consists of 3 linearly equations which are KCL equations, KVL equations and branch equations. The set of the electric variables (voltages and currents) of each cell is connected to the variables of the adjacent cells by invoking Kirchhoff's law on mesh and nodal equations [19]. Jabbehdari and Mariscotti modeled a 3-dimensional railway configuration system in MATLAB. The model of stray current distributing model with lumped parameters can be used to calculate step voltages around grounded power systems and the performance of a grounding system in terms of resistance to earth, which is useful for transient events such as fault currents in particular lightning strokes [19].

In summary, stray current distributing simulation in Simulink is based resistor network and has the characteristics of discretization. However, as discussed above, it can be seen that the the influencing factor analyzed by the matlab simulation is more simplified, which is far from the actual operation conditions.

6.3 CDEGS

CDEGS (current distribution, electromagnetic field, grounding and soil structure analysis) is a set of powerful integrated software tool, which can be used to accurately analyze the grounding, electromagnetic field and electromagnetic interference problem. As a kind of boundary element platform, it can realize the modeling of infrastructure component in the tunnel and evaluate the performance of stray current.

Cotton *et al* studied the stray current control from the perspective of stray current collection system design and efficiency firstly. Specifically, the effect of concrete water content, stray current collector cable cross-sectional area and soil resistivity on the SCCM efficiency is analyzed. Cotton *et al* constructed a geometrically accurate model of the system by CDEGS, which is composed of running rails, stray current collector cable and civil/stray current mat. Simulation results showed that: the efficiency of SCCM increases with the increasing soil resistivity and the increasing stray current collector cable cross-sectional area; as the stray current collector cable cross-sectional area increases, the percentage of current in the SCCC increases compared to the part in the SCCM; the increase of water content in the SCCM also improve the efficiency of SCCM [59,60]. The study of Cotton *et al* reveals the relationship between the efficiency of SCCM and the influencing factor of stray current and provides theoretical guidance for SCCM controlling the leakage amount of stray current. However, the CDEGS model is relatively simple, which only includes running rails, stray current collector cable and stray current collection mat.

On the basis of the previous research, relatively complete subway dc traction model is built based on CDEGS, and many studies were conducted. From the perspective of tunnel geometry and topology, Charalambos *et al* analyzed the stray current distribution in rectangular tunnel and shield tunnel under the complex environment by CDEGS. In this simulation, 2-dimensional distribution of net leakage current stray current collection grid (SCCG) and current remained SCCG were obtained, then each part of the current content in the dc transit system was calculated and stray current levels was evaluated by estimating stray current density on reinforcement and longitudinal voltage drop on reinforcement [61]. Because the parameters in the model is more close to the actual situation, the evaluation results are more reliable. Charalambos *et al* studied the dynamic distribution of stray current on cut-and-cover sections of dc subway systems. Dynamic simulation model was built to calculate dynamic stray current, with every element in the matrix to restore stray current at different location and time [62]. Spatial distribution of gross leakage charge SCCG and the corrosion influence under actual circumstances were evaluated with CDEGS model. The gross leakage charge $CQ1c$(Rails) along the whole section from the time $t1$ to $t2$ is calculated by adding the gross leakage charge $Q1c(Ln)$, which is calculated by integrating the corrosive stray current Icsc with the specific time limits, as is given in the following:

$$CQ_{lc}\left(\text{Rails}\right)=\int_{t_1}^{t_2} I_{\text{csc}}\left(t,L_1\right)+\int_{t_1}^{t_2}\left(t,L_2\right)+\ldots+\int_{t_1}^{t_2}\left(t,L_n\right) \tag{3}$$

The same method is portable to other working conditions, such as the shield tunnel and the light rail system. In the above two kinds of tunnel model, each component in the model is one-to-one correspondence with the soil layer, and is equivalent to metallic conductor with different size. The 3-dimensional stray current modeling study conducted by Charalambos *et al* provides a method to evaluate stray current negative effect from the perspective of geometric structure, which has important reference value for further quantitative analysis of stray current on the 3-dimansional tunnel structure.

Furtherly, Charalambos *et al* built a cross-track regeneration model with two bored tunnels. Each part of the current content in the dc transit system are calculated, and the effect of energization scenario on the stray current densities is analyzed. It turned out that: compared with the base scenario, the rail potential increases under the cross-track regeneration (50-50) scenario; the efficiency of SCCS greatly decreases, and with the increase of the power percentage of regenerating track drawing, the efficiency decreases and stray current density of regenerating track increases. Charalambos *et al* put forward the mitigation measures to this phenomenon: linking the stray current collection cables (SCCCs) of each tunnel by conductors, and studied the effect of number of SCCC cross bonds along bored tunnel system (BTS). Simulation results showed that: tunnel-to-tunnel cross-bonding (through SCCC) could be a valuable tool to reinstate the benefits of a stray current collection system; the use of two cross bonds at either ends of the system will suffice [63]. The use of more SCCC cross bonds will not significantly improve the efficiency of the collection system.

Soil resistivity distribution has great influence on the stray current distribution, which is the most important environmental factor of stray current corrosion. Factors that affects soil resistivity are: salt content and composition, water content, soil texture, soil firmness, soil temperature, etc. Therefore, the soil model is needed to determine in the process of modeling. The existing soil model mainly includes homogeneous soil model, horizontal layered soil, vertical layered soil, composite layered soil, etc. Concrete ballast bed will crack due to the reinforcement corrosion expansion, and soil resistivity distribution has great influence on the service life of ballast bed. Regarding this as the cutting point, Charalambos and Cotton *et al* c the effect of soil resistivity distribution on the corrosion performance, and compared the distribution of current leakage density and corrosive leakage charge on the track bed and metallic pipe with different soil models. Soil models used in simulation is shown in Fig. 17. Two parameters were put forward to evaluate the metal loss distribution and corrosive life distribution of the pipeline, which were corrosion rate and the depth of steel corrosion required to cause cracking of the contrete. Charalambos *et al* drew the conclusion that the performance of trackbed when used as a stray current-collection system is highly dependent on the soil structure. From the perspective of drainage efficiency, compared with the homogeneous soil, the efficiency of SCCM greatly increases with the increased resistivity in deeper soil layer. From the perspective of service life, a concentrated current-leakage region will exist on the pipe and trackbed when a vertical-soil model exists, which will lead to the risk of being corroded [64].

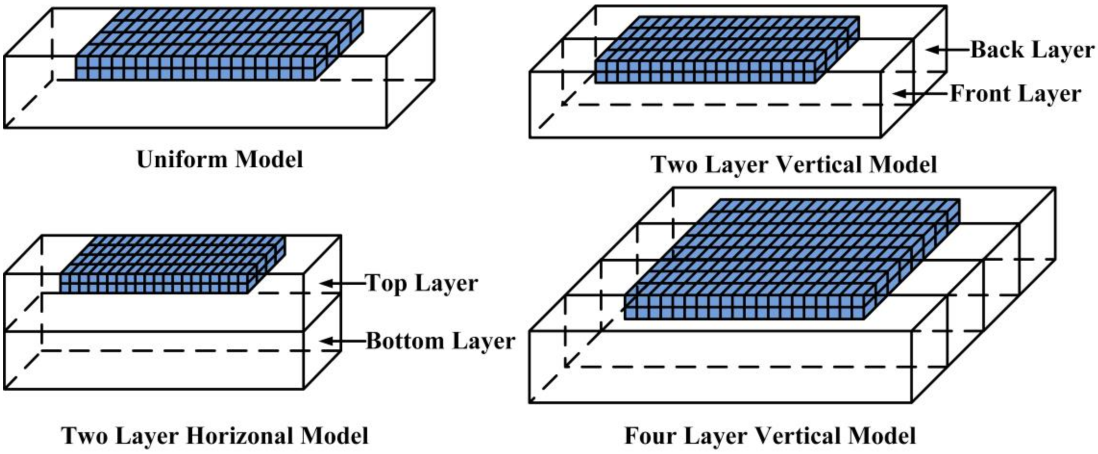

Figure 17. Soil models employed in simulations.

Based on this, Charalambos *et al* developed a model employing a resistive network to solve the stray current distribution found analyzed the impact of soil topologies on the stray current distribution and buried metallic structure service life by CDEGS, which is the coupling between a light rail system and buried third-party infrastructureThe simulation results of net current leakage on the track beds and third-party utility conducted by MATLAB and CDEGS were compared in two models (resistive-type network for the double-track floating system with substations same end and opposite end). In this model, algorithm was designed to determine the gross leakage charge of the rails, track beds and third-party utility structure. It turned out that: different soil models influence the corrosion performance of the rail, track bed, and metallic pipe; in a uniform soil environment, severe corrosion on pipelines predominates in sections where there is a low earth resistivity; the horizontally layered soils where the earth resistivity shows a decrease with depth are dominated by the behavior of the upper layer; for vertical models, a concentrated current leakage region will exist on the third-party utility structure and track bed at the point where the soil discontinuity occurs [65]. Charalambos *et al* analyzed the characteristics of stray current distribution under different soil model. The proposed model can be used to optimize stray current protection required along the locomotive running direction and the design of current collection scheme.

According to the described literature, it can be seen that the stray current can be analyzed comprehensively by simulation model based on CEDGS from several aspects below:

1. the effects of tunnel structure on the performance of stray current;
2. the performance of stray current in different part of the tunnel;
3. rail insulation and grounding scheme;
4. the impacts of stray current on the third-party infrastructure like buried pipeline and metallic structure.

Through CDEGS, stray current distribution in the tunnel space can be evaluated from the aspects such as the insulation resistance of tunnel service and reinforcement in the segment ring, soil resistivity distribution, and the efficiency of SCCM, which is more intuitive and convenient than using FEM in 3-dimensional current distributing analysis.

In summary, different simulation methods have different characteristics, but all can analyze the stray current distribution under the actual engineering environment. Compared with the mathematical model of stray current, the parameters are more complex, thus the corrosion hazard of stray current can be evaluated through of a variety of methods. Many scholars have carried on the simulation research to the performance of the SCCM. But the performance of SCCM is still unsatisfactory in actual engineering operation, which is closely related to the structure of SCCM. Through the existing analytical methods and simulation methods, the optimization of the SCCM remains to be furtherly studied to improve the drainage efficiency of SCCM in actual engineering operation.

7. CONCLUSION AND PROSPECT

With the wide application of subway dc traction system in the urban traffic, the negative effect generated by the stray current gets more and more attention. Therefore, many scholars studied subway stray current distributing model, and some study results have been applied in the engineering system. Building such model has contributed to clearing the main factors influencing the amount of stray current leakage, and providing theoretical basis and guidance for designing subway lines (rational layout of substations and platforms, reasonable planning of power supply interval length), stray current collection scheme (relationship between related resistance and current leakage amount), grounding scheme, daily maintenance of lines (keeping rails clean and dry).

For the actual dc traction reflux system, the results of existing models show a big difference with actual numerical value. Therefore, the purpose of calculating in the existing models is analyzing the effect of various factors on stray current distribution qualitatively and providing guidance of stray current protection in theory.

In summary, in view of the existing research status of stray current distributing model, the limitations of existing studies mainly embody in following 4 aspects:

1. Due to the uncertainty of the current flow, the stray current affects not only the buried pipeline, but also corrodes the metallic structure around subway. The analytical domain of existing

stray current distributing model mainly focuses on the 2-dimensional plane, which can only be used to calculate the corrosion performance of buried pipeline under the rail, but unable to evaluate the effect of stray current on the metallic tunnel structure outside the subway.

2. The existing stray current distributing analysis is based on the known parameters. However, parameters like longitudinal rail resistance and rail-to-earth resistance will change in different area along the lines. As a consequence, there will be a difference between analytical results and actual situation from the viewpoint of engineering practice.

3. The existing reflux system and SCCM are designed based on the traditional stray current distributing model. The reinforcement is uniformly distributed in the SCCM, but the stray current is non-uniformly distributed in the rail plane. As a consequence, the existing SCCM and reflux system remain to be optimized.

4. The subway stray current distributing model is the basis of analyzing rail potential distribution and choosing grounding scheme. The existing studies is mainly based on the resistor network model. The limitation of resistor network model will lead to the limitation of evaluating rail potential. Many problems like the too frequent operation and misoperation of OVPD, the too high rail potential still exists.

Depending on the limitations above, the research of stray current distributing model in the future mainly focused on the following 3 aspects:

1. 3-dimensional stray current distributing model research

How to build a 3-dimensional stray current distributing model accurately is a problem need to be solved in the future study. Traditional 2-dimensional model ignores the effect of current flow in multiple directions on the buried metallic structure. Traditional 2-dimensional is used to analyze corrosion performance of buried pipeline under the running rail, but cannot evaluate the influence scope of stray current correctly. Building 3-dimensional model is conducive to analyzing the effect of stray current on the metallic structure around the subway and calculating the potential at any point underground accurately. In this way, the computational domain will not only be limited to the area under the running rail, but also in other directions. The existing 3-dimensional stray current distributing research are mainly concentrated on ANSYS, BESAY and CDEGS, but using 3-dimensional stray current model to do accurate quantitative analysis is still in the blank stage. The quantitative calculation of 3-dimensional subway stray current distribution is more close to ground current actual state of diversion. Therefore, the quantitative calculation of 3-dimensional subway stray current distribution will be the development trend and direction of stray current research in the future, which can be used furtherly to optimize the corrective operation of OVPD, the control of rail potential and the monitor of stray current.

2. Rail-to-earth resistance evaluation research

How to evaluate rail-to-earth resistance in operation sections is a problem need to be solved in the future study. Through the existing data, the damage area of rail-to-earth insulation and pipeline coating are determined, and the distribution of pipeline-to-earth resistance and rail-to-earth resistance are also obtained. According to the distribution, the rail insulation receives targeted maintenance firstly, and the current distributing calculation accuracy of mathematical model is improved by plugging in the distributing parameters. Meanwhile, it should be pointed out that the theory and the measurement method of rail-to-earth resistance need to be studied furtherly due to the inaccurate existing measurement method. By means of optimizing the parameters of the rail-to-earth resistance, the calculation accuracy of the stray current distribution model can be furtherly improved.

3. Reflux system and SCCM optimization research

How to optimize the reflux system and SCCM is a problem need to be solved in the future study. The existing structure of reflux system and SCCM is based on the resistor network model of stray current and the engineering experience, the effect of which is not satisfatory in actual operations. Therefore, both need to be optimized. The optimization design of the structure of reflux system and SCCM is conducted 3-dimensional distribution of subway stray current, which will improve the efficiency of SCCM. On the other hand, the optimization design of both should not change the other aspect of performance and won't be more complicated in engineering construction as much as possible.

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