Effect of Soil Salt Content on Stray Current Distribution in Urban Rail Transit

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ABSTRACT In order to study the effect of soil salt content on the stray current distribution in the urban rail transit, a three-layer stray current resistance network distribution model of "rail-drainage net-ground" is established based on the method of resistance network. The mathematical model is established by using the equivalent circuit of micro-element, and the analytical expressions of voltage and current of each metal structure are derived. Then, the simulation model is established with MATLAB/Simulink software, and the simulation results are consistent with the analytical results. A small-scale experimental platform corresponding to the model is built, and the changes of leakage current and the stray current in soil samples with different NaCl content are measured. The experimental results show that the leakage current and stray current in soil samples increases with the increase of NaCl content. Finally, the experimental results are verified by the established simulation model and the simulation results are basically consistent with the experimental results, which proves the accuracy of the experimental results. The research results can provide a theoretical basis for the protection design of subway stray current.

INDEX TERMS Leakage current, resistance network, salt content, stray current, urban rail transit

I. INTRODUCTION

Urban rail transit has been widely used in large and medium-sized cities due to its advantages of high speed, short departure time, large traffic volume, high safety and reliability, and green environmental protection, which has played a major role in improving the urban traffic environment [1]. The DC traction power supply system for urban rail transit supplies power to trains through the traction network, and returns along the rail. However, due to the limitation of the operating environment, technical conditions, and other factors, the rail cannot be absolutely insulated from the ground, which leads to the leakage of a part of traction return from the rail and forms stray current [2][3]. When the stray current flows through the reinforced concrete, the buried metal, and the urban pipes network system near the line, electrochemical corrosion will occur. And it will invade the urban power grid through the grounded transformer node, resulting in DC magnetic bias of the transformer and other problems, and causing economic losses and potential safety hazards [4][5][6][7]. Therefore, studying the distribution laws of the stray current and the relative factors can provide a theoretical basis for the design of the stray current corrosion protection, and it is of great significance to ensure the long-term and safe operation of rail transit.

Since the emergence of the subway, the problem of DC stray current has been widely concerned, and scholars from various countries have successively carried out a large number of studies on the stray current and corrosion problems caused by the stray current. In recent years, several landmark studies have proposed a power electronic dynamic simulation experimental platform based on a bidirectional variable resistance module and a traction power supply system based on a negative resistance converter. And the experiment platform and the traction power supply system can simulate and measure the dynamic distribution of stray current and rail potential of trains under different operating conditions and different grounding systems [8][9][10][11]. There are also many scholars who have studied the distribution of stray current and rail potential by various simulation software and algorithms. For example, a long line stray current simulation modelling method based on CDEGS software was proposed, which can accurately and efficiently calculate the stray current of the long line of DC metro systems [12]. Besides, a calculation method of the stray current based on the infinitesimal algorithm under the condition of multiple power supply source sections was...
proposed [13]. Some studies have calculated and measured the surface potential gradient around the subway road based on the finite element method, and determined the corrosion range of stray current, which provides a theoretical basis for reducing the corrosion of existing buried pipelines and selecting the location of new pipelines [14]. Some scholars established a mathematical model and adopted the finite element method to quantitatively calculate the subway stray current filed in homogeneous and layered dielectrics, which provides a basis for determining the protection range of stray current and quantitatively evaluating the impact of stray current on the surrounding underground environment [15].

The electric train model with traction substation, running rail and third rail in MATLAB/Simulink was simulated, and compared the size and distribution of stray current under the conditions of different soil types with or without collecting pads. In addition, the corresponding simulation and modelling system was verified by the experiments on the accuracy of the actual electrified railway condition [16].

A large number of scholars have studied the influencing factors of stray current. For example, a study established a simulation model to study the influence of the transition resistance of the rail-to-ground on the distribution of stray current [17], and the results show that the stray current leaking from the rail increases with the decrease of the rail-to-ground transition resistance. Some scholars studied the influence of different vehicle operation modes on the distribution of rail potential and stray current [18], and the results show that the rail potential and stray current generated by the trains under acceleration and braking modes are significantly higher than the running mode of sliding and uniform speed. And when the train runs between different traction substations, the rail potential at the train position obtains the maximum value. The effects of various parameters on the corrosion of reinforced concrete structures by DC stray current and the interaction of various factors were studied through numerical calculation [19]. The results show that the external source and internal source have different effects on the corrosion of metal structures caused by stray current, which is basically determined by the resistivity configuration of the whole system. The stray current model of the DC traction system was established by using two new modelling techniques to study the influence of the variation of various parameters on the distribution of stray current and rail potential [20]. Besides, many scholars have carried out a lot of researches on the metal corrosion in ionic solution when DC stray current exists. For example, the electrochemical effect of DC stray current on the low carbon steel and Cr steel in saturated Ca(OH)₂ solution was studied [21]. The results show that the intensity of stray current has a great influence on steel corrosion, and the presence of a small amount of chloride will reduce the intensity of stray current required for steel corrosion. The corrosion of reinforced concrete under the coupling action of stray current and chloride ion was studied [22]. The results show that the larger the stray current and the chloride ion concentration is, and the longer the corrosion time is, the more serious the corrosion of reinforced structure in concrete is. Several scholars studied the influence of DC stray current on the corrosion of steel bar in the cracked shield tunnel [23]. The results show that the corrosion rate in the steel pipe section is related to the current input mode and the distance between the steel and the cracking place. Besides, the influence of anions in the soil on the corrosion rate of carbon steel was studied [24], and the experimental results show that the corrosion rate of carbon steel increases with the increase of anions in soil.

Through the analysis of the current research status of stray current at home and abroad, it can be found that up to now, some literatures evaluate the stray current and rail potential through some simulation software and calculation methods, so as to obtain some distribution laws of stray current and rail potential, and build a small experimental platform to verify the conclusions. Some literatures study the law of DC stray current corrosion of metal structure, so as to provide a theoretical basis for preventing the corrosion of buried metal. Other literatures study some influencing factors of stray current and rail potential, and their influences on the distribution of stray current and rail potential. Most literatures mention that the rail-to-ground transition resistance has great influence on stray current distribution, but there is little research on the influence of soil physical and chemical properties on stray current distribution in urban rail transit. Therefore, this paper mainly studies the influence of soil salt content on stray current distribution, in order to provide reference for the design of subway stray current interference protection.

II. MATHEMATICAL MODEL AND DERIVATION OF STRAY CURRENT

A. THE ESTABLISHMENT OF MATHEMATICAL MODEL

The traction substation is equivalent to the DC power supply, and each metal structure is equivalent to a resistance network, then a uniform three-layer stray current resistance distribution model of "rail-drainage net-ground" is established [25]. As shown In Fig. 1, where $L$ is the distance from the locomotive to the traction substation; $x$ is the distance from any point to the traction substation; $I$ is the locomotive traction current; $i_p$ is the current of the rail; $i_p$ is the current of the drainage net. Current $I$ is injected into the rail at $L$. Because it is impossible to completely insulate between the rail and the ground, part of the current enters the drainage net and the ground through the track bed, and finally flows back to the rail and the negative pole of the traction substation. The part of the current that fails to return to the traction substation according to the established return path is called stray current.

B. ANALYTIC COMPUTATIONAL EXPRESSION
Take a micro-element equivalent circuit as shown in Fig. 2, where $R_i$ is the longitudinal resistance of the rail; $R_p$ is the longitudinal resistance of the drainage net; $R_g$ is the rail-to-drainage net transition resistance; $R_{g1}$ is the drainage net-to-ground transition resistance; $u_x$ is the voltage of the rail-to-drain net, hereinafter referred to as rail potential; $u_p$ is the voltage of the drain net-to-ground, hereinafter referred to as drain net potential, and the current leaking into the earth is considered in this model.

The following differential equations can be obtained by sorting the above equations:

$$\begin{align*}
\frac{du_x}{dx} &= i_t R_i - i_p R_p \\
\frac{di_t}{dx} &= u_x \\
\frac{du_p}{dx} &= i_p R_p \\
\frac{di_p}{dx} &= u_p - u_x \\
R_i \frac{di_t}{dx} + u_x &= du_x + u_x \\
R_p i_p dx + u_p &= du_p + u_p \\
i_p - R_p \frac{dx}{du_p} dx &= u_p + du_p
\end{align*}$$

where

$$\begin{align*}
\lambda_1 &= \sqrt{\frac{1}{2} \left( \frac{R_i + R_p}{R_g} + \frac{R_p}{R_{g1}} \right) + \sqrt{\left( \frac{R_i + R_p}{R_g} + \frac{R_p}{R_{g1}} \right)^2 - 4 \frac{R_i R_p}{R_g R_{g1}}}} \\
\lambda_2 &= \sqrt{\frac{1}{2} \left( \frac{R_i + R_p}{R_g} + \frac{R_p}{R_{g1}} \right) - \sqrt{\left( \frac{R_i + R_p}{R_g} + \frac{R_p}{R_{g1}} \right)^2 - 4 \frac{R_i R_p}{R_g R_{g1}}} \\
k_1 &= \frac{R_i - \lambda_2^2 R_g}{R_p} \\
k_2 &= \frac{R_i - \lambda_2^2 R_g}{R_p} \\
k_3 &= (k_1 + 1) \lambda_1 \\
k_4 &= (k_2 + 1) \lambda_2
\end{align*}$$

The boundary conditions under ideal conditions are:

$$\begin{align*}
\begin{cases}
i_t(0) = 1 \\
i_t(L) = 0 \\
i_p(0) = 1 \\
i_p(L) = 0
\end{cases}
\end{align*}$$

Bringing in the ideal boundary conditions, the coefficients are obtained as follows:


\[
c_1 = \frac{b_1 I}{1 + e^{\lambda_1 L}} \\
c_2 = \frac{b_1 I e^{\lambda_1 L}}{1 + e^{\lambda_1 L}} \\
c_3 = \frac{b_2 I}{1 + e^{\lambda_2 L}} \\
c_4 = \frac{b_2 I e^{\lambda_2 L}}{1 + e^{\lambda_2 L}}
\]

where

\[
b_1 = \frac{R_c - \lambda_2^2 R_g}{\left(\lambda_1^2 - \lambda_2^2\right) R_g} \\
b_2 = \frac{R_c - \lambda_2^2 R_g}{\left(\lambda_2^2 - \lambda_1^2\right) R_g}
\]

According to the above calculation, the current leaking into the earth can be obtained as \( I - I_i - i_p \), hereinafter referred to as the stray current in the ground.

III. MATLAB SIMULATION MODEL

A. THE ESTABLISHMENT OF SIMULATION MODEL

According to the mathematical model established above, the simulation model of a uniform three-layer structure of "rail-drainage net-ground" is established by using the Simulink module in MATLAB software. In the established model, the traction substation is equivalent to the DC power supply, and each metal structure is equivalent to a resistance network. The relevant simulation components are used to measure the current of rail, the current of the drainage network, the rail potential, the drainage network potential, and the stray current in the ground. In the established simulation model, the values of the parameters are as follows: the interval length is 1 km, the longitudinal resistance of the running rail is 0.1 Ω/km, the longitudinal resistance of the drainage network is 0.4 Ω/km, the rail-to-drainage net transition resistance is 40 Ω·km, and the drainage net-to-ground transition resistance is 0.1 Ω·km. The parameters in the simulation are selected according to References [17] and [25]. The values of the simulation parameters are basically the same as the values of each structure in the actual operation, which are within the appropriate value range of the simulation parameters.

B. COMPARATIVE RESULTS BETWEEN ANALYTICAL CALCULATION AND SIMULATION

In order to verify the reliability and accuracy of the simulation model, the values of each parameter in the simulation substitute into the analytical expression based on the mathematical model, that is, the values of the corresponding parameters in the simulation and analytical expressions are equal. Then, the results obtained by the analytical expression are compared with the results obtained by the simulation, as shown in Fig. 3(a)-(e), which are the analytical and simulation comparison diagrams of the current of the rail current, the rail potential, the current of the drainage net, the drainage net potential, and the current in the ground, respectively.

It can be seen from Fig. 3 (a, b, c and e) that the analytical results of the current of rail, the rail potential, the current of drainage net, and the current in the ground are in good consistent with the simulation results. From Fig. 3d, we can find that the analytical results of the drainage net potential are basically consistent with the simulation results, but there are some deviations. The reason for the deviation is that there is a slight deviation between the model parameter calculation and the analytical calculation model that comes from the simulation software. The maximum difference between the analytical results and the simulation results is 4.056 mV, and the minimum difference is 0.102 mV, that is, the maximum difference does not exceed 4.1 mV, which is basically negligible. Based on the above analysis, it can be confirmed that the simulation model established in this paper is accurate and reliable.

V. EXPERIMENT ON THE INFLUENCE OF SOIL SALINITY ON THE DISTRIBUTION OF STRAY CURRENT

A. EXPERIMENT PREPARATION

The traction substation is equivalent to the DC power supply, and the rail, drainage net and ground are equivalent to resistances. Then a small-scale experiment platform is built. Experimental circuit as shown in Fig. 4. In the experiment, the values of the parameters in the model are as follows: the longitudinal resistance of the rail is 0.25 Ω/cm, the longitudinal resistance of the drainage network is 0.25 Ω/cm, and the rail-to-drainage net transition resistance is 0.1Ω. Since the drainage net-to-ground transition resistance is mainly related to the soil resistivity. Therefore, the resistivity of the soil is changed by adding NaCl into the soil, so as to change the drainage net-to-ground transition resistance, and then observe the influence of NaCl content on the stray current distribution.

The stray current test system of the rail-drainage net-ground model is built in the laboratory, and the experimental device diagram is shown in Fig. 5. The soil sample used in the experiment is the loam soil. In the experiment, the size of the container where the soil is placed is 45*35*30 cm. The Faithtech FT10010 linear DC power supply is used to simulate the power supply of the traction substation. Its output voltage scope is 0 ~ 100V, the output current scope is 0 ~ 10A, and the resolution is 100 mV and 100 mA respectively. The resistors with different resistance values are connected into a resistance network module by welding. One end of a metal probe with a length of 5 cm and a radius of 1 mm is inserted into the soil, and the other end is connected with the data acquisition module, with a distance of 4 cm.
(a) rail current

(b) rail potential

(c) drainage net current

(d) drainage net potential

(e) stray current in ground

FIGURE 3. Comparison between analytical results and simulation results

FIGURE 4. Experimental circuit

FIGURE 5. Experimental device
between every two probes. The distance between the locomotive and the traction substation is 40cm. The data acquisition module selected is the DAQM-4202 data acquisition module of Zhouzheng Technology, which has a working voltage of 7-36 VDC, an accuracy level of ±1‰, and a resolution of 16 bits. The instrument used to measure soil salt content is TPY-8A soil nutrient rapid tester, as shown in Fig. 6. It is an 8-channel soil nutrient rapid tester, which can detect soil parameters such as nitrogen, phosphorus, potassium, pH, organic matter, salt content and other soil parameters. The measuring range for soil salt content is 0 ~ 23ms/cm, and the accuracy is ±2%FS.

In the experiment, when the resistance value is too small, the current flowing through the wire will be too large and the wire will be burned. When the resistance value is too large, the ground leakage current will be too small to be measured. Therefore, due to the limitations of the experimental condition, the value in the experiment can’t be reduced by equal ratio. That is, the parameters of the resistance network model used in the experiment are selected according to the laboratory conditions, which makes it different from the actual situation. But this study discusses the influence of soil salt content on the stray current distribution in urban rail transit. When measuring the leakage current under different salt content, the experimental devices are the same. In other words, in each experiment, the difference is the salt content of the soil, and other conditions are the same. Therefore, the final conclusion that the effect of soil salt content on stray current distribution in urban rail transit is reliable.

**B. EXPERIMENT METHOD**

Firstly, the soil sample without NaCl is measured. Before the measurement, 100g soil sample is taken out, then the salt content of the sample is detected by the soil nutrient tester, and it is found that the salt content of the soil samples is 0ms/cm. Then the DC stabilized power supply of the simulated traction substation is adjusted to 0.3A, 0.6A, 0.9A, 1.2A and 1.5A, respectively. And the corresponding leakage current is measured and the corresponding stray current is calculated according to the leakage current. The calculation method is that the total stray current is equal to the sum of leakage currents at each measuring point. Then the measured data are sorted and calculated, and the Origin software is used to draw the graphs of the leakage current and stray current in the ground with respect to the distance between the measuring point and the traction substation.

Origin is a scientific drawing and data analysis software developed by OriginLab, which supports running under Microsoft Windows. Origin supports various 2D or 3D graphics. The data analysis functions in Origin include statistics, signal processing, curve fitting and peak analysis. The curve fitting in Origin uses the nonlinear least squares fitting based on Leverberg-Marquardt algorithm. Origin’s powerful data import function supports multiple formats of data and various graphic output formats. Origin is a graphical user interface software with a spreadsheet front end. Different from the common spreadsheet software, its worksheet takes columns as objects, and each column has corresponding attributes and other user-defined identifiers. In addition, Origin uses the column formula instead of the data unit formula for calculation.

After the measurement of the original soil sample, 15g NaCl is added to the soil, then is stirred evenly. And 100g sample is taken to measure its salt content by the soil nutrient tester. The previous experimental steps are repeated until 150g NaCl is added. The salt content of the soil in the experiment is designed according to reference [26], because this reference has studied the salt content of different soil types in Lanzhou [26]. Therefore, the research in this paper can largely conform to the actual situation in Lanzhou, and provide reference for stray current corrosion protection of Lanzhou Metro Line 1 and the newly-built line.

**C. INFLUENCE OF NaCl CONTENT ON STRAY CURRENT DISTRIBUTION**

The resistivity of soil is affected by several parameters, among which the water content, temperature, porosity, chemical composition and salt content of soil are more affected [27][28][29][30]. Therefore, these factors are considered in the experiment. Firstly, in order to minimize the influence of moisture changes on the experimental results, necessary measures are taken to prevent evaporation, so as to keep the moisture content basically constant during the test. Secondly, there is only one soil sample used in the experiment, and the salt content of the soil is changed by gradually adding the same amount of NaCl to the soil sample, so other chemical composition and porosity of the soil sample in the experiment are the same, which will not affect the experimental results. Finally, in order to control the possible errors caused by temperature in the experiment, the laboratory temperature is kept constant during the test. Therefore, in this experiment, only the influence of the change of soil salt content on the leakage current and stray current in the soil is discussed.
FIGURE 7. traction current is 0.3A

FIGURE 8. traction current is 0.6A

FIGURE 9. traction current is 0.9A

FIGURE 10. traction current is 1.2A
When 30g NaCl is added to the soil sample, changing the traction current to 0.3A, 0.6A, 0.9A, 1.2A and 1.5A, respectively, the leakage current and stray current are plotted against the distance from the measuring point to the traction substation. When 60g, 90g, 120g and 150g NaCl are added to the soil sample, respectively, the above tests are repeated. The experimental results are shown in Fig. 7-11.

In Fig. 7, the traction current is 0.3A, when 0g, 30g, 60g, 90g, 120g and 150g NaCl are added into the soil sample, the corresponding maximum value of the leakage current in the ground are 0.108 mA, 0.225 mA, 0.486 mA, 0.547 mA, 0.59 mA and 0.714 mA, respectively, as shown in Fig. 7a. And the corresponding maximum value of the stray current is 0.241 mA, 0.504 mA, 0.844 mA, 1.074 mA, 1.142 mA and 1.322 mA, respectively, as shown in Fig. 7b. In Fig. 10, when the traction current reaches 1.2A, the maximum value of the leakage current in the ground corresponding to 0g, 30g, 60g, 90g, 120g and 150 added to the soil sample are 1.004mA, 1.915 mA, 2.375 mA, 3.16mA, 3.648 mA and 4.051mA, respectively, as shown in Fig. 10a. And the corresponding maximum value of the stray current are 1.908 mA, 4.645mA, 5.888mA, 7.246mA, 8.304 mA and 9.541 mA, respectively, as shown in Fig. 10b. Doing the same analysis on the stray current and the leakage current in the ground under the 0.6A, 0.9A and 1.5A traction current, it is obvious that both the leakage current and the stray current in the ground increase with the increase of salt content.

D. INFLUENCE OF TRACTION CURRENT ON STRAY CURRENT DISTRIBUTION

In the experiment, the distribution of stray current with different salt content is measured when the traction current is 0.3A, 0.6A, 0.9A, 1.2A and 1.5A, respectively. In order to study the influence of traction current on the distribution of the stray current, soil sample without NaCl and soil sample with 150g NaCl are selected as research objects. And the distribution of leakage current and stray current under different traction currents are plotted, as shown in Fig. 12 and Fig. 13.

It can be seen from the Fig. 12 that when the salt content is 0g and the traction current is 0.3A, 0.6A, 0.9A, 1.2A and 1.5A, respectively, the maximum value of the leakage current is 0.108mA, 0.311mA, 0.621 mA, 1.004 mA and 1.29 mA, respectively, as shown in Fig. 12a. And the corresponding maximum value of the stray current is 0.239 mA, 0.658 mA, 1.166 mA, 1.908 mA and 2.415 mA, respectively, as shown in Fig. 12b. When the salt content is 150g, the distribution of the leakage current and the stray current in the earth is shown in Fig. 13, and the same analysis is made. It can be obtained that the stray current and the leakage current in the ground increase with the increase of the traction current.
VI. SIMULATION VERIFICATION

In the experiment, the conductivity of soil samples with different contents of NaCl can be measured by the soil nutrient tester, so the drainage net-to-ground transition resistance can be obtained. The reason why the conductivity of soil should be converted into resistance is that in the mathematical model and simulation model established, the electrical conductivity between drainage net and the ground is represented by rail-drainage net transition resistance. And in the experimental platform, resistors with different resistance values are also used to simulate various metal structures. Therefore, in the final verification stage, the measured soil conductivity needs to be converted into resistance to verify the experimental results. The values of the various parameters in the experimental model are substituted into the simulation model, in which the transition resistance between the drainage network and the ground is calculated according to the conductivity of soil samples with different contents of NaCl. In the experiment, the traction current is set to 1.5A. And the soil samples without NaCl, 30g NaCl and 60g NaCl are selected as the verification objects. The soil conductivity of the three samples is 0 ms/cm (This value may be caused by the insufficient precision of the soil nutrient tester and irregular operation during the measurement process.), 0.18ms/cm and 4.7ms/cm, respectively. Set each parameter in the simulation as the

FIGURE 13. With the addition of 60g NaCl in soil sample

FIGURE 14. Without NaCl in soil sample

FIGURE 15. With the addition of 30g NaCl in soil sample

FIGURE 16. With the addition of 60g NaCl in soil sample

FIGURE 17. Different NaCl content
number of experiments, and compare the results, as shown in Fig. 14-17. Fig. 14-17 show the comparison results of the experiment and simulation under three conditions of adding 0g NaCl, 30g NaCl and 60g NaCl into the soil sample. It can be seen that the simulation results are basically consistent with the experimental results, but there is still a slight deviation. The possible reasons for the deviation are that the precision of the measuring elements in experimental equipment is different from that in simulation; the selection of measurement points does not reach the completely equidistant arrangement in the process of the experiment; and the soil samples are not stirred until they are completely uniform after adding NaCl into the soil sample due to the limitation of the experimental conditions. However, the maximum difference between the simulation results and the experimental results does not exceed 0.056mA in Fig. 12, and the maximum difference between the simulation results and the experimental results does not exceed 0.409 mA in Fig. 13, and not more than 1.138 mA in Fig. 14. The maximum value of relative error is under 7.8%. Therefore, the difference between the experimental results and the simulation results is basically consistent. Finally, the simulation results of the three conditions are compared when NaCl is 0 g, 30 g and 60 g added in the soil, respectively. As shown in Figure 14, it can be found that the stray current increases with the increase of NaCl content in soil samples, which is consistent with the experimental results.

VII. CONCLUSIONS

In this paper, the three-layer stray current resistance distribution of "rail-drainage network-earth" is established, as a mathematical model, a simulation model and a small-scale experimental platform. The influence of the NaCl content in soil sample on the distribution of the stray current is studied. Through the measurement of stray current in soil sample with different NaCl content and the simulation verification, it can be found that the leakage current and the stray current in soil samples is strongly influenced by NaCl content. In other words, the leakage current and the stray current in the soil sample increase with the increase of NaCl content. In addition, the influence of different traction current on the distribution of the leakage current and the stray current is also studied in the experiment. The results show that the leakage current and the stray current increase with the increase of the traction current. The experimental design takes into account the actual situation in Lanzhou area, and the experimental results provide reference for stray current corrosion protection of Lanzhou Metro Line 1 and the newly-built line.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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